Bionomics, behaviour and control of the codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), in pome fruit orchards in South Africa

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DECLARATION

I, the undersigned, hereby declare that the work contained in this dissertation is my own original work and has not previously, in its entirety or in part, been submitted at any university for a degree.

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OPSOMMING

Kodlingmot (*Cydia pomonella)* is reeds sedert die vorige eeu 'n sleutelplaag van kernvrugte. Ten spyte van die hoë ekonomiese profiel, is daar min kennis betreffende die bionomie en gedrag van hierdie plaag in appelboorde in Suid-Afrika. Hierdie inligting is noodsaaklik vir die ontwikkeling van 'n volhoubare geïntegreerde bestuursprogram.

Tydens veldproewe is 'n korrelasie tussen die tyd van die jaar en eierlegging in die boonste of onderste helfte van bome gevind. Eerste-generasie motte het betekenisvol meer eiers in die onderste helfte van die bome gelê, terwyl tweede- en derde-generasie motte meer eiers in die boonste helfte van die bome gelê het. In toenemende volgorde was die voorkeur eierleggingsposisies op Granny Smith (GS) en Golden Delicious (GD) appels die blare, vrugte en hout. Meer eiers is op vrugte van GS spore (35.6%) as op dié van GD spore (10.7%) gelê. Op vrugspore was daar 'n betekenisvolle toename in aantal eiers op GD blare en GS vrugte deur die seisoen, terwyl die getal eiers op GS blare en GD vrugte konstant gebly het. Op takke was daar 'n toename in aantal eiers op GD en GS blare, maar nie op vrugte of hout nie. Die voorkeur eierleggingsposisie op vrugte was die fovea van die steelaanhegting en die wang rondom die fovea. Die verspreiding tussen verskillende vrugdraende klasse (1 – 4 vrugte per spoor) was slegs in die een-vrug-per-spoor klas ewekansig, terwyl daar in die ander spoorklasse groepering voorgekom het.

In laboratoriumstudies van embrioniese en onvolwasse stadia is 'n lineêre verband tussen ontwikkelingskoers en konstante temperature van 15, 17, 20, 25 en 30°C±1°C gevind. Die onderste drempel-temperature vir embrioniese, larwale en papie-ontwikkeling was onderskeidelik 11.1°C, 7.9°C en 9.9°C. Graaddae benodig vir voltooiing van embrioniese, larwale en papie-ontwikkeling was onderskeidelik 80.5, 345 en 279. Die respons van verskillende stadia by konstante temperature het ooreengestem met hul respons onder wisselende temperature.

Motte het nie gepaar nie en min eiers is gelê by temperature onder 16°C of bo 27°C. Die lewensverwagting van motte het afgeneem met toename in temperatuur. Seisoenale variasie in lewensverwagting en eierlegging het voorgekom by konstante sowel as wisselende temperature. By konstante temperature het somer-volwassenes betekenisvol meer eiers as lente-volwassenes geproduseer.

By 'n konstante temperatuur van 25°C, sowel as by wisselende temperature, het vyf duidelik onderskeibare larwale instars voorgekom. Die ooreenkoms tussen die gemiddelde kopkapsule-wydte en wydte-reeks vir elke instar wat op vrugte van verskillende stadiums van ontwikkeling by

wisselende temperature geteel is, dui daarop dat vrugontwikkeling en temperatuur weinig invloed op gemiddelde kopkapsule-wydte het.

Tydens mou-hok studies in die boord is geen betekenisvolle verskil in die fekunditeit van lente- en somer-motte waargeneem nie. Vroeg in Oktober het lente-motte betekenisvol meer eiers as in November geproduseer. Eiermortaliteit het van 8.2% in die lente tot 21.2% in die somer toegeneem. Faling van 1ste instar larwes om vrugte te penetreer het van 4.9% tot 19.5% gewissel, terwyl mortaliteit van larwes vanaf uitbroei tot uitkoms uit die vrug van 29.7% tot 42.9% gewissel het. Mortaliteit van 5de instar larwes na uitkoms uit die vrug het van 0% tot 8.7% gewissel, en papie-mortaliteit van 0% tot 3.5%.

Op groot, 27-jaar oue bome is meer oorwinterende larwes op Golden Delicious (13.9) as op Granny Smith (5.7) gevind, en meer as 70% van die larwes op beide kultivars is op snoeiwonde gevind. Op klein, 7-jaar oue bome was die gemiddelde aantal larwes op Golden Delicious en Granny Smith-bome 0.5 en 2.0 onderskeidelik.

'n Gekombineerde paringsontwrigting- en insekdoder beheerprogram het weerstandbiedende kodlingmot-populasies verminder tot 'n vlak waar minimum tot geen insekdoder-toedienings vir verskeie seisoene gemaak is. Die effektiwiteit van 'n feromoon-gebaseerde strategie, aantal feromoonbehandelings, aantal vrystellers/ha en vlak van insekdoder-toediening word sterk deur heersende weersomstandighede beïnvloed. Die rande het hoër vruginfestasie as die middel getoon in boorde onder paringsontwrigting sowel as boorde onder insekdoder-programme. Die teenwoordigheid van minerale olie op blare en takke het geen nadelige effek op eierlegging gehad nie en dit het geen betekenisvolle eierdodende effek gehad nie. Indien die olie ná eierlegging toegedien is, is daar wel 'n betekenisvolle eierdodende effek waargeneem. Tydens veldproewe het insekdoders met laer effektiwiteit as die primêre insekdoder, azinfos-metiel, aanvaarbare beheer verskaf indien dit suksesvol geïnkorporeer is in 'n spuitprogram deur 'n beleid van afwisseling van insekdoders oor generasies.

Die kleinste variasie tussen die aantal graaddae tussen biofix en eerste uitbroei van eiers is gevind indien die tweede lokvalvangs as biofix gebruik is. 'n Biofix gebaseer op die eerste aand na die eerste lokval vangste wat die temperatuur 17°C of hoër was teen 18:00, het ook 'n kleiner variasie getoon as die eerste lokvalvangs. Die aantal graaddae tussen die tweede en derde vlug biofix het tussen 531.2 en 488.87°D gewissel, met 'n gemiddelde van 508.1°D.

ABSTRACT

The codling moth, *Cydia pomonella* (L.) has been a major pest of pome fruits since before the turn of the last century. However, despite its high economic profile little is known about the bionomics and behaviour of this pest in apple orchards in South Africa, information required for the development of a sustainable integrated management programme.

In field trials there was contingency between the time of year and the upper and lower half of the tree. First generation moths laid significantly more eggs in the bottom half of the tree while second and third generation moths laid significantly more eggs in the top half of the tree. The preferred oviposition sites on Granny Smith (GS) and Golden Delicious (GD) cultivars, in order of preference, were leaves, fruit and wood. More eggs were laid on the fruit of GS spurs (35.6 %) than on those of GD spurs (10.7 %). On fruit spurs there was a significant increase in the number of eggs on GD leaves and GS fruit over the season, whereas the number of eggs on GS leaves and GD fruit remained constant. On branches there was an increase in the number of eggs on GD and GS leaves, but not on the fruit or wood. The preferred oviposition site on the fruit was the fovea of the stalk insertion and the rounded cheek area surrounding the fovea. The distribution within different fruit bearing classes (1 - 4 fruit per spur) was random only for one fruit per spur, while on the other spur classes clustering occurred.

In laboratory studies of the embryonic and immature stages there was a linear relationship between rate of development and constant temperatures of 15, 17, 20, 25 and 30°C ± 1°C. The lower threshold temperatures for embryonic, larval and pupal development were 11.1, 7.9, 9.9°C respectively. The degree-days required to complete embryonic, larval and pupal development were 80.5, 345, and 279 respectively. The response of the different stages to constant temperatures was similar to that under fluctuating temperatures.

At temperatures below 16°C or abouve 27°C moths did not mate and few eggs were laid. Moth longevity decreased with increasing temperature. There was seasonal variation in longevity and oviposition at constant and fluctuating temperatures. Summer adults produced significantly more eggs than spring adults at constant temperatures.

At a constant temperature of 25°C and fluctuating temperatures there were five distinct larval instars. The similarity between the mean head capsule width and ranges for each instar reared on fruit of

different stages of development at fluctuating temperatures indicates that fruit development and temperature have little influence on mean head capsule width.

From sleeve-cage studies in the orchard there was no significant difference in the fecundity of spring and summer moths. In the beginning of October spring moths produced significantly fewer eggs than in November. Egg mortality increased from 8.2 % in spring to 21.2 % in summer. Failure of 1st instar larvae to penetrate the fruit ranged from 4.9 % to 19.5 %, while mortality of larvae from egg hatch to emergence from the fruit ranged from 29.7 % to 42.9 %. Mortality of 5th instar larvae after emerging from the apples ranged from 0 % to 8.7 % and pupal mortality from 0 % to 3.5 %.

On large 27-year old trees more overwintering larvaewere found on Golden Delicious (13.9) than on Granny Smith trees (5.7), with over 70 % of larvae being found in pruning wounds on both cultivars. On small 7-year old Golden Delicious and Granny Smith trees the mean number of larvae was 0.5 and 2.0 per tree.

A combined mating disruption and insecticide control programme reduced codling moth resistant populations to levels requiring a minimum to no insecticide intervention for several seasons. The efficacy of a pheromone based strategy, number of pheromone treatments, number of dispensers/ha and level of insecticide intervention required are strongly influenced by prevailing weather conditions. Fruit infestation in orchards under a mating disruption programme and under an insecticide programme were greater along the borders compared to the interior.

The presence of horticultural mineral oil on the leaves and branches did not have a detrimental effect on oviposition nor was there any significant ovicidal effect. A significant ovicidal effect was obtained when applied after oviposition. In field trials, insecticides with lower levels of efficacy than the primary insecticide, azinphos-methyl, provided acceptable control when successfully incorporated into a spray programme which followed a policy of alternation of insecticides across generations.

The least variation in the number of degree-days between biofix and first egg hatch of the spring flight was when the second trap catch (Biofix 2) was used as the biofix. A biofix based on the first evening when the temperature reached or exceeded 17°C at 18:00 after first trap catch also showed less variation than when the biofix was based on first trap catch. The mean number of degree-days accumulated between Biofix 2 and first egg hatch was found to be 139.1° D. The number of degree-days between the first and second flight biofixes varied between 531.2 and 488.87°D with a mean of 508.1°D.

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CONTENTS

GENERAL INTRODUCTION

The codling moth, *Cydia pomonella* (L.), has remained a key pest of pome fruits in South Africa for over 100 years (Petty 1926; Myburgh *et al.* 1973; Nel 1983). It was first reported in South Africa from Graaf-Reinett around 1885 spreading rapidly to other apple and pear production areas in Constantia, Claremont, Capetown and Wellington (Lounsbury 1898). Although attempts were made to limit the spread of this pest through legislation, by 1909 few areas of the Cape were free of codling moth and it had spread north into the Orange Free State and Transvaal (Lounsbury 1909). By 1918 it was concluded that nearly all areas in South Africa, where apples and pears were commercially grown, were infested with codling moth (Lounsbury 1918).

From the onset producers have struggled to control codling moth. Over a century ago Lounsbury (1898) said of *C. pomonella*, "The measures for the suppression of codling moth are not as simple as the dipping of sheep. Spraying to be done effectively must be done not only thoroughly but at a certain time - the proper time varying with the local conditions and with the season, and not determinable with exactitude without watching the development of the young fruit." From this quotation it would appear that little has changed over the past 100 years. Many of the earlier studies concentrated on the control of this pest by means of barriers, orchard hygiene (Lounsbury 1898, 1904, Van der Merwe 1912, Lounsbury & Faure 1918; Pettey 1916, 1921, 1923, 1926,1932) and chemical sprays (Pettey 1921, 1923, 1926, 1930, 1932; Pettey & Mossop 1930; Stubbings & Nel 1939; Stubbings & Hattingh 1945).

Despite its economic importance as a major pest of pome fruits little was known about its oviposition behaviour on apples in South African pome fruit orchards prior to this study. All the earlier studies on oviposition were confined to pears (Nel 1941; Hattingh 1942, 1943). There was also a lack of detailed information of the biology of this pest with respect to temperature effects on the embryonic and immature stages, the longevity, oviposition and mating of spring and summer generation moths. In 1985 studies were commenced to further our understanding of the ovipositional behaviour and biology of this pest with the aim of improving the management of codling moth in apple orchards. The information on the oviposition of codling moth on Granny Smith and Golden Delicious apples has already been published (Blomefield *et al.* 1997).

During this study it became evident that codling moth populations were developing resistance to the primary insecticides used to control it (Blomefield 1994). Similar observations were being made in other pome fruit producing areas of the world (Varela *et al.* 1993, Knight *et al.* 1994). These developments prompted an extension of this study to include the evaluation of a phenology model, technologies and insecticides in resistance management programmes that would reduce the use of insecticides and the pome fruit industry's reliance on insecticides, particularly organophosphate insecticides.

The development of resistance to the primary insecticides has compelled researchers and agrochemical companies to develop and promote management practices that are less disruptive to orchard ecosystems. It is hoped that the results of this study will further our understanding of codling moth behaviour in South African pome fruit orchards, and lead to more effective, economical control of this key pest of pome fruits.

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1. FIELD OBSERVATIONS ON OVIPOSITION OF CODLING MOTH, *CYDIA POMONELLA* (LINNAEUS) (LEPIDOPTERA:TORTRICIDAE), IN AN UNSPRAYED APPLE ORCHARD IN SOUTH AFRICA

ABSTRACT

Oviposition of the codling moth, *Cydia pomonella* (Linnaeus), was studied from 1985 to 1989 in unsprayed apple orchards on the Elgin Experiment Farm, Grabouw, Western Cape Province. There was contingency between the time of year and level (upper half, lower half) in the tree. First generation moths laid significantly more eggs in the bottom half of the tree while second and third generation moths laid significantly more eggs in the top half of the tree. During the first generation moth flight significantly more of the eggs from the lower half of the tree were laid on the southern and western aspects. On the upper half of the tree there were no significant differences in the number of eggs laid between the four compass points. During the second and third generation moth flights there were no significant differences in the number of eggs laid between the compass points in the lower or upper half of the tree respectively. The preferred oviposition sites on Granny Smith (GS) and Golden Delicious (GD) cultivars, in order of preference, were leaves, fruit and wood. More eggs were laid on the fruit of GS spurs (35.6 %) than on those of GD spurs (10.7 %). On fruit spurs there was a significant increase in the number of eggs on GD leaves, and GS fruit during the season, whereas the number of eggs on GS leaves and GD fruit remained constant. On branches there was an increase in the number of eggs on GD and GS leaves, but not on the fruit or wood. The distribution within different fruit bearing classes (1 - 4 fruit per spur) was random only for one fruit per spur, while on the other spur classes clustering occurred.

1.1 INTRODUCTION

Codling moth, *Cydia pomonella* (Linnaeus)(Lepidoptera:Tortricidae), is a major pest of apples and pears and, to a lesser extent, of apricots in South Africa and many other countries. It is occasionally found in other stone fruits such as peaches and plums (Blomefield 1989). Despite its economic, importance little is known about its oviposition behaviour on apples in South African orchards. Concern about the possible effects of routine chemical spraying on human health and the environment, has compelled researchers and agrochemical companies to develop and promote management practices that are less disruptive to orchard ecosystems. The management of codling moth has

consequently shifted from a strictly chemical to a multi-faceted approach that also incorporates horticultural practices such as pruning and thinning. Although these practices are primarily aimed at producing a healthy, productive fruit tree, they may also improve control of the pest through habitat management. Emphasis is placed on the minimum use of pesticides that have a disruptive impact on the beneficial arthropods present in apple orchards. The toxicity of synthetic pyrethroids to beneficials, the increasing number of pest species that are developing resistance to pyrethroids (Croft 1989) and the development of codling moth resistance to azinphos-methyl (Varela *et al.* 1993) have resulted in a growing interest in the benzoylphenylureas (BPU's) with their ovicidal activity (Purcell & Granett 1986; Badowska-Czubik *et al.* 1991). These products have a good environmental profile and are less disruptive to beneficial arthropods than the conventional insecticides currently in use (Croft 1990).

These factors have highlighted the importance of a thorough knowledge of codling moth oviposition behaviour. The aim of this study was to collect detailed information on oviposition sites, and to investigate quantitative differences and seasonal changes with respect to these sites, using fruit spurs and branches as sampling units. The influence of fruit density on oviposition behaviour was also studied. This chapter presents the results and observations from 1985 to 1989 on codling moth oviposition under unsprayed conditions.

1.2 MATERIAL AND METHODS

1.2.1 Study sites

Studies were conducted in two orchards on the Elgin Experiment Farm, 1km north of Grabouw at (34.09S and 19.02E) at an elevation of 305 m. The average annual rainfall at this locality over a 27-year period was 1049.6 mm and the average annual temperature over a 23-year period was 15.2°C. One study site (A) was a 27-year-old, 0.7 ha orchard consisting of 200 trees with a 6.10 x 6.10 m spacing, 20 trees long and 10 trees wide. There were 180 Golden Delicious (GD) trees and 20 Granny Smith (GS) trees in a 9:1 planting. The trees were 3 - 4 m high. Insecticides had been used on only two occasions during the past 15 years, where 10 trees in the orchard were treated with azinpos-methyl. The other study site (B) was a seven-year-old, 0.9 ha orchard, consisting of predominantly GS, GD and Topred (TR) apple cultivars. The planting distance was 3 x 5 m, and the trees were 2 - 3 m high. The orchard had never been sprayed to control codling moth.

Two types of sampling units were used in the study, fruit spurs and branches. A fruit spur is defined as a sub-unit of a branch and consists of a short woody stalk, referred to as the wood of the fruit spur, the leaves plus leaf petioles and fruit including the stalk of the fruit. A branch consists of a stem, twigs and fruit and leaf spurs. The stem, twigs and leaf and fruit stalks are referred to as the wood of the branch. The leaf spur may include a terminal twig but no fruit.

1.2.2 Oviposition: aspect and elevation

During the seasons from 9 October 1985 to 9 April 1996, 16 fruit spurs were collected weekly at random from 10 randomly selected GD trees in orchard A. Two spurs were removed from the top and two from the middle at each of the four compass points of the sample trees. The fruit spurs were placed in plastic bags in an ice chest and transported to the laboratory where they were stored in a coldroom at 12°C ± 1°C and examined within three days. Hatched and live eggs were recorded separately until 5 February 1986, thereafter they were grouped together. The location of the eggs on various parts of the fruit spurs (on the spur wood, the upper and lower leaf surface, and fruit) was recorded.

Correspondence analysis (Greenacre & Vrba 1984) was used to determine whether there were similarities in egg numbers between different positions, and if there was correspondence between position and time of year. Positions on the trees were represented by the columns of the data matrix and the rows were the 26-weekly live egg counts. The early-season period (first moth flight; 16/10/1985 - 11/12/1985) and late-season period (second and third moth flights; 11/12/1985 - 9/4/1986) were used as supplementary row variables. The point of division of the season into two periods was based on commencement of emergence of second generation moths from fifth instar larvae collected weekly in corrugated cardboard bands placed around the branches of GS trees, and the seasonal oviposition pattern obtained from fruit-spur samples (Fig. 1). The data were also analysed for contingency between time of year (early season, and late season) and level (top or bottom).

1.2.3 Oviposition on fruit spurs

During the 1986/87 and 1987/88 seasons 20 GD and 20 GS trees were selected for sampling fruit spurs in orchard A. Each GD sample-tree was selected at random from the eight GD trees adjacent

to each GS tree. The same trees were sampled throughout the season. Sampling was carried out weekly in both seasons except during 1986/87, the sampling interval for GS trees being extended to two weeks after 19 January 1987. On each sample date, eight randomly selected fruit spurs were removed from each designated sample tree, placed in plastic bags and stored at 12°C ± 1°C until examination. Eggs were recorded as hatched or live and the location of the eggs was recorded. A split-split plot analysis of variance with cultivar as main plot, time as sub-plot and location as sub-sub-plot was performed on the numbers of live eggs (Table 7). The three factor interaction (cultivar, time and location) was broken down into single degree polynomials over time to investigate possible trends (Table 7). Slopes and intercepts of linear regression lines on dependant (live eggs) over independant variables (time) were fitted for cultivar and location combinations and subjected to a 2 × 2 factorial analysis of variance with factors two cultivars and two locations (Table 8) (Snedecor & Cochran 1980). In instances where significant differences were not found, data were combined. Similar analyses were done on the ratios of the eggs on the fruit to those on leaves, and the ratio of eggs on the lower surfaces to that on the upper leaf surfaces. Before the analyses, data were transformed using $y = \sqrt{X + 0.375}$ (Zar 1984) to stabilize the variances.

The number of apples on each fruit spur was also recorded. With respect to oviposition on the fruit, the fruit was divided into six equal sections from the stalk (upper) to calyx (lower) end. Sections 1, 2 and 3 represented the first three upper sections and 4, 5 and 6 the lower three sections of the fruit. Data were analysed by using a weighted logit analysis of variance with the PC-Plum program (Randall 1989). This program uses the generalized linear model (McCullagh & Nelder 1983) to analyse data on an ordinal scale. In this case the ordinal data were generated by categorizing each egg according to the section of the apple on which it was laid, making it possible to estimate the mean egg-section for each year and each cultivar. Total number of eggs per segment was also compared, using Student's *t*-test.

During the 1988/89 and 1989/90 seasons, commencing in January, 80 to 100 fruit spurs, one spur per tree, were randomly selected weekly for four weeks from two rows of TR apple trees. The data were analysed for contingency between cultivar and leaf surface (upper and lower).

To examine differences in leaf pubesence among cultivars, a fruit spur was randomly chosen from each of four GS, GD and TR trees in orchard B during November and again in April. The third basal leaf on the new shoot growth of the fruit spur was removed from each spur and a disc 0.39 cm in diameter

was cut with a corkborer (No.4) from the middle of the leaf between the lateral veins and 0.5 cm from the midvein. Each disc was microscopically examined at x400 times magnification. The trichomes on both the upper and lower surfaces were counted and then individually removed using forceps to determine the average number of trichomes/cm^2.

1.2.4 Oviposition on branches

During the 1987/88 and 1988/89 seasons two branches, 30 - 50 cm in length and 1.5 - 2.0 cm in diameter, were selected at random on each of the 20 GD and 20 GS sample-trees in orchard A, marked with a plastic tag and inspected at weekly intervals. In 1987/88 only one branch per tree was inspected after 15 December 1987. The wood, leaves (upper and lower surface) and fruit were inspected for eggs *in situ*. Eggs were recorded as hatched or live. The oviposition site, whether on a leaf, the wood or fruit, and direct distance of the egg from the nearest fruit were also recorded. All eggs, whether hatched or live, were then removed. Newly emerged larvae that had entered the side of fruit were killed to reduce fruit losses from the branches.

A split-split plot analysis of variance with cultivar as main plot, time as sub-plot and location as sub-sub-plot was performed on the numbers of live eggs (Table 10). The two factor interaction (cultivar and location) was broken down into single degree polynomials over time to investigate possible trends. Slopes and intercepts of linear regression lines on dependant (eggs) over independant variables (time) were fitted for each location (leaves and wood and fruit). Before the analyses the data were first transformed using $y = \sqrt{X + 0.375}$ (Zar 1984). The ratios of eggs on fruit to those on leaves, eggs on fruit to those on wood, and eggs on wood to those on leaves were also calculated and analysed. The data were analysed for contingency between time of year and leaf surface (upper or lower). The total number of branches was used as a weighing coefficient to compensate for the unequal number of branches inspected for eggs.

1.2.5 Oviposition on fruit spurs of various fruit densities

From 15 January 1990 to 20 February 1990 spurs with one, two, three and four fruit per spur were selected weekly from each of five GD trees selected at random from each of eight rows in orchard A. Over the six-week period a total of 240 spurs of each spur class was selected. The fruit spurs were inspected for eggs which were classified as hatched or live. The distribution of eggs was investigated

by testing the following null hypotheses originally presented by Jackson (1979):

Hypothesis 1 (Jackson's 1B): the distribution of eggs among fruit spurs of various fruit densities is random and not influenced by the number of fruit per spur.

Hypothesis 2 (Jackson's 1C): when fruits alone are considered, the distribution of eggs among spurs of various spur classes is not random, the number of eggs per spur depending on the number of apples per spur. A four-fruit spur will thus have four times the number of eggs found on a one-fruit spur.

Hypothesis 3 (Jackson's 2): within spur classes the distribution of the eggs per spur is random (*i.e.* conforms to a Poisson distribution).

All three hypotheses were tested by comparing the data with the appropriate models using a chi-square goodness-of-fit test. In the case of hypothesis 3, a χ^2-test for agreement with the negative binomial distribution was performed where the data did not conform to the Poisson distribution. Classes were combined when expected frequencies were less than one (Snedecor & Cochran 1980).

1.3 RESULTS

1.3.1 Oviposition: aspect and elevation

A total of 2 761 eggs was recorded on 4 160 fruit spurs, of which 572 were live and 2 189 had hatched. The preferred oviposition site was leaves, with 81.4 % of the eggs, then fruit with 17.5 %, and wood with 1.1 %. On leaves, the lower surface was the preferred site with 69.4 % of the eggs. The first egg was recorded on leaves on the bottom south side of the tree on 16 October 1985. The first egg recorded on fruit was on 20 November 1990. At that time the mean diameter of the fruit was 2.66 cm (SD ± 0.37; n = 157). Although live eggs comprised only 20.7 % of the recorded eggs, hatched eggs were not included in oviposition studies in view of their variable persistence and the possible differential effect weather conditions (rain and wind) could have on dislodging them, and on the physiological processes of the tree, such as leaf drop in the different study areas. Live eggs also reflected a very recent pattern of oviposition, the incubation period varying from approximately 6 - 15 days depending on the time of the season.

The results of the correspondence analysis presented in Fig. 2 show the projection of the position of eggs laid onto the first principle axis (29.6 % of the inertia). The points on the axis reveal a marked separation of the height at which eggs were laid (top or bottom half of the tree). The egg counts from the bottom of the tree are to the left of the centroid, while those from the top of the tree are to the right of the centroid. In addition, the eggs of the early-season period lie to the left of the centroid and are associated with the bottom of the tree while those of the late-season period are to the right of the centroid and are associated with the top of the tree.

Table 1 provide the data for total eggs laid in the top and bottom halves of the tree during the early and late parts of the season. There is contingency between level (top or bottom) and period (χ^2 = 15.39; $P < 0.001$) with significantly more eggs in the bottom half during the early period ($\chi^2 = 10.32$; $P = 0.001$), and significantly more in the top half during the late period ($\chi^2 = 8.26$; $P = 0.004$). These analyses confirm the results of the correspondence analyses.

Although more eggs were recorded during the early-season period (Fig. 3) on the southern and western aspects of the tree (data from both height levels combined), the differences between the various compass points were not significant ($\chi^2 = 5.37$; $P = 0.146$). However, when the data from each level were analysed separately there were significantly more eggs on the bottom half of the western and southern aspects ($\chi^2 = 8.0$; $P = 0.046$). On the top half of the tree there were no differences in egg numbers between the four compass points ($\chi^2 = 0.34$; $P = 0.952$).

During late season, egg numbers on the various aspects were not significantly different ($\chi^2 = 3.63$; $P = 0.304$). Although fewer eggs were recorded on the northern aspect in the top half of the tree the differences were not significant ($\chi^2 = 7.77$; $P = 0.051$). In the bottom half of the tree egg numbers tended to be spread equally among the four aspects ($\chi^2 = 0.94$; $P = 0.816$).

1.3.2 Oviposition on fruit spurs

During 1986, 739 hatched and 232 live eggs were recorded from 4 000 GD fruit spurs, and 687 hatched and 244 live eggs from 3 200 GS spurs. In 1987, 4 000 fruit spurs of each cultivar were inspected. There were 1 785 hatched and 381 live eggs from GD spurs, and 1 532 hatched and 278 live eggs were recorded from GS spurs. In both years more than 73% of the eggs had hatched.

During the 1986 season the first eggs were recorded on GS leaves on 20 October and about three weeks later, on 10 November, on GD leaves. The first egg recorded on a GS fruit was a hatched egg on 24 November and a live egg on 1 December, whereas on GD fruit the first egg recorded was a hatched egg on 15 December. The trend for earlier oviposition on GS rather than on GD in 1987 was similar to that in 1986. The first eggs recorded were on GS leaves on 19 October and on GD leaves on 26 October. The first eggs recorded on the fruit were two live eggs on GS on 23 November and one live egg on GD on 30 November.

The average number of live eggs per spur for both years was very low, particularly for the first generation (Tables 2, 3). In 1986 very few live eggs were found on GD (5.8 %) and GS (7.6 %) spurs, whereas in 1987 the percentage of GD (9.5 %) and GS (7.0 %) spurs with eggs was also very low. During both years most of the eggs were deposited individually but in some cases there were two or three, and on two occasions 11, eggs laid on one spur. If hatched eggs are included, there was an increase in the mean number of eggs per GD and GS spur. There was also a higher number of spurs with 2-4 eggs per spur.

The oviposition sites on fruit spurs in order of preference were leaves, fruit and wood (Table 4). During the first generation most of the eggs were laid on the leaves, few were recorded on the fruit and none on the wood. During the second and third generations a greater proportion of the eggs were laid on the fruit. Only one egg was recorded on a fruit stalk and one live egg was recorded on the wood of the fruit spur. During the two years only one live egg was recorded on spur wood of GD. The average length of wood per spur for GS was 1.9 cm and that for GD 3.4 cm.

Over the two years an average of 89.1 % and 64.4 % of the eggs on GD and GS spurs respectively were oviposited on the leaves. Most of the eggs on GD leaves were laid on the lower surface (69.8 %), while on GS leaves most were laid on the upper surface (72.9 %). More eggs were laid on the fruit of GS spurs (35.6 %) than on GD spurs (10.8 %). The observation that the lower surface of GD leaves and the upper surface of GS leaves were the preferred oviposition sites on leaves was confirmed by significant chi-square values for contingency between cultivar and surface (upper and lower) of the leaf in 1986 ($\chi^2 = 39.23$; $P < 0.001$) and in 1987 ($\chi^2 = 110.45$; $P < 0.001$).

The distribution of live eggs on TR spurs is shown in Table 5. In both years the preferred oviposition site was the leaves on which more than 74.9 % of the eggs were deposited. There was a difference

between upper and lower surfaces in 1989 ($\chi^2 = 6.23$; $P = 0.013$) with more eggs laid on the upper surface, whereas in 1990 more or less equal proportions were deposited on each leaf surface ($\chi^2 = 0.34$; $P = 0.56$). Similar proportions of eggs were recorded on the fruit in both years. Few eggs were laid on the wood of the spur.

The high proportion of eggs recorded on the upper surface of GS leaves was probably due to the higher pilosity of the lower leaf surface (Table 6). Based on the combined data from November and April the lower leaf surface of GS was 15.4 and 1.6 times more pubescent than GD and TR respectively while the upper leaf surface of GS was 131 and 5.5 times more pubescent than GD and TR respectively. The upper surface of GS and lower surface of GD were similar in degree of pubescence.

There was a significant linear interaction ($P = 0.0041$) between cultivar, location and time, while the higher order polynomial interaction effect involving these three variables was not significant (Table 7). Therefore, the linear interactions were examined using linear regression. The intercepts were significantly different for location (Table 8, $P = 0.0437$), but not for cultivar. The intercepts for cultivars were therefore combined, but not those for location. In the case of the slopes, significant interaction occurred ($P = 0.0439$), and were therefore not combined. The slopes of the lines for eggs laid on GD leaves and on GS fruit versus time were significant, indicating an increase in number of eggs laid as the season progressed (Fig. 4). There was no significant increase in egg numbers on GD fruit and GS leaves over time. The difference between the intercepts for location indicated that more eggs were laid on the leaves compared to the fruit at the beginning of the season. The ratio of the number of eggs laid on the fruit to those laid on leaves (Y) increased linearly with time (X) on GS ($Y = 0.2 + 0.035X$; $t_{14} = 3.23$, $P = 0.006$) indicating an increased preference for fruit as an oviposition site with time. This was not the case on GD as the regression was not significant.

The ratio of the total number of eggs recorded on the lower surface to those recorded on the upper surface of GD leaves was 1.380 and 0.543 on GS leaves. These ratios, however, did not differ significantly ($t_1 = 3.77$, $P = 0.165$). When this ratio (Y) was regressed on time (X) a significant quadratic relationship ($Y = 0.16X - 0.01X^2$; $t_{30} = 6.20$, $P < 0.001$) was found for the combined data. The ratio increased up to week 16, and then decreased towards the end of the season.

In total, significantly more eggs were recorded on GS (86.5) than GD (27.5) apples ($t_2 = 7.71$, P

= 0.016). However, the analysis using PC Plum showed that years ($P = 0.471$) and cultivars ($P = 0.850$) did not differ significantly with respect to mean egg-section. For GS the mean section was two for both years, and for GD the mean section was three for 1986/1987 and one for 1987/1988.

1.3.3 Oviposition on branches

In 1987, 430 eggs were recorded on GS branches, of which 309 were live and 121 hatched. On GD branches, 213 live and 146 hatched were recorded giving a total of 359 eggs. In 1988, 931 eggs, 731 live and 200 hatched, were recorded on GS branches and 1 120 eggs, 834 live and 286 hatched, on GD branches.

Eggs were recorded on the first sampling date of 26 October 1987. On GS branches 37 live and 7 hatched eggs were recorded, all the hatched eggs occurring on the wood. Of the live eggs, 11 and 26 occurred on the leaves and wood, respectively. On the GD branches 11 live eggs and one hatched egg were recorded. Of the live eggs eight and three were recorded on the leaves and wood, respectively. In 1988 the first sampling date was on 20 October. On the GS branches 15 live eggs and four hatched eggs were recorded, all the hatched eggs occurring on the wood. Of the live eggs four and 11occurred on the leaves and wood, respectively. On GD branches only one live egg was recorded on a leaf.

The distribution of the eggs on the leaves (upper and lower surfaces), fruit and wood for both cultivars during 1987 and 1988 is shown in Table 9. An average of 87.8 % of the eggs on GD branches were laid on the leaves. Over the entire sampling period the number of eggs on the fruit (7.0 %) and wood (5.3 %) of the GD branches remained very similar. Although the leaves on GS branches were also the preferred oviposition site (73.7 %) during the two years, a high proportion of eggs of the first generation were laid on the wood (32.1 %). Most of the eggs on GD leaves were laid on the lower surface (70.6 %) while on GS leaves most were laid on the upper surface (60.8 %). The observation that the bottom surface of GD leaves and the upper surface of GS leaves were the preferred oviposition surfaces on the leaves of the two cultivars is confirmed by chi-square values for contingency between cultivar and surface of the leaf in 1987 ($\chi^2 = 80.00$; $P < 0.001$) and in 1988 ($\chi^2 = 94.87$; $P < 0.001$).

The cultivars did not differ significantly with respect to the number of eggs laid on branches, but there

was a significant interaction between location and time for eggs recorded weekly on the leaves, wood and fruit (Table 10). These interactions were examined using linear regressions of $y = \sqrt{Number\ of\ eggs} + 0.375$ versus time.

The slopes and intercepts for wood and fruit did not differ (slope $t_{78} = 1.070$, $P = 0.288$; intercept $t_{78} = 1.095$, $P = 0.277$) and the data were therefore combined. The intercepts for number of eggs laid on the leaves, and on fruit and wood did not differ significantly ($t_{78} = 0.3663$; $P = 0.7151$) (Fig. 5) indicating that the number of eggs laid on the leaves and on fruit and wood were initially the same. As the season progressed there was a significant increase in the number of eggs laid on the leaves ($t_{82} = 2.51$, $P < 0.001$) and in the number of eggs found on the wood and fruit ($t_{82} = 2.81$, $P = 0.0014$). However, the slope for the line for leaves was greater than that for fruit and wood ($t_{78} = 3.62$; $P < 0.001$) indicating a more rapid increase in eggs laid on leaves than on fruit and wood. There was no significant difference for the ratio of eggs on fruit to wood surfaces. However, the ratio of the eggs found on the wood to leaf and fruit to leaf surfaces was not constant over the entire season ($P < 0.05$). During the first three weeks of the sampling period more eggs were deposited on the wood than the leaves of GS branches. As the season progressed there was a swing in oviposition preference on the GS branches with more eggs being laid on the leaves than the wood. On the GD branches the ratio of eggs on the wood to leaves remained constant over the sampling period.

The distributions of live and hatched eggs on fruit and leaf spurs around the nearest apple were similar for GS and GD apples (Fig.6). However, it appeared that there was a tendency for eggs to be laid closer to GS fruit than GD fruit. Hatched eggs were included as these were no more than a week old, the eggs being removed after their location and distance from the fruit had been recorded. On GS branches, 82.4 % and 96.1 % of the eggs were found within 6 cm and 12 cm of the fruit respectively, while on GD branches, 62.4 % and 96,0 % of the eggs were found within 6 cm and 12 cm of the fruit.

On GS branches, 27.5 % and 72.5 % of eggs were found on leaf and fruit spurs respectively, while on GD the percentages were 24.7 and 75.3 respectively. The chi-square value for contingency between the type of spur (leaf or fruit) and cultivar (GS or GD) was not significant ($\chi^2 = 0.08$; $P = 0.78$). However, significantly more eggs were laid on the fruit than leaf spurs on GS ($\chi^2 = 68.32$; $P < 0.001$) and GD ($\chi^2 = 61.8$; $P < 0.001$) branches.

1.3.4 Oviposition on fruit spurs with various fruit densities

When testing the first hypothesis (*Jackson's 1B*), *i.e.* that the distribution of eggs is not influenced by the number of fruit per spur, it was found that the expected values differed significantly from the observed values, resulting in rejection of the hypothesis (Table 10). However, under the second hypothesis (*Jackson's 1C*), which states that when fruits alone are considered, the distribution of eggs among various fruit densities is not random, the expected values were not significantly different from the observed values (Table 11). Therefore, the distribution of eggs among spurs with different fruit densities was not random, but related to the number of fruit on the spur. The average number of eggs per spur (Y) (for all spur classes) increased linearly with an increase in the number of fruit per spur (X) ($Y = 0.0545 + 0.2036X$; $P < 0.001$).

In the case of the third hypothesis (*Jackson's 2*), *i.e.* that within classes the distribution of the eggs is random, only in the case of the class 1 spur (one fruit per spur) did the Poisson distribution ($P >$ O,05) fit, indicating a random distribution of the eggs (Table 12). The other spur classes fitted a negative binomial distribution ($P > 0,05$) indicating clumped distribution of the eggs . Spurs with more than one fruit often had more than one egg.

1.4 DISCUSSION

1.4.1 Aspect and elevation

There were significant ovipositional differences with respect to aspect and elevation. Moths of the first generation laid significantly more eggs on the bottom southern and western aspects of the tree. First generation moths also laid significantly more eggs in the bottom half of the tree, while those of the second and third generations laid significantly more eggs in the top half. The findings are similar to those of previous researchers. Although Geier (1963), Wood (1965) and Blago & Dickler (1990) reported no ovipositional difference with respect to aspect, MacLellan (1962) observed an early-season preference for the southeast portion of the tree. Summerland & Steiner (1943), MacLellan (1962) and Geier (1963) reported a tendency for more eggs to be recorded in the tops of the trees. Richardson & DuChanois (1950) also observed an increase in larval damage with elevation, an expression of egg distribution, on trees between 3.0 and 3.7 m high. Jackson (1979) found no difference with respect to elevation despite the trees being between 12 and 20 m tall. A possible

reason for the difference in the findings is that in the Western Cape, blossoming begins in the bottom half, and generally the southern aspect, and extends to the top. This blossoming pattern is more noticeable in GD than GS trees (Bergh, pers. comm.). Coupled with the blossoming pattern of the tree is the fact that, under South African conditions, codling moth adults begin to emerge very early in the season. In 1985, 61.1 % of the spring generation emerged before full-bloom. This led to the presence of high numbers of moths in the orchard before GD trees reached full-bloom. The presence of a greater number of blossoms and later more advanced fruitlets in the bottom half of the tree early in the season may influence the oviposition behaviour of codling moth. In areas where most of the moths of the first generation emerge after blossom, these infestation patterns would not be as evident (Beers *et al.* 1993). The study also showed that only during the first half of the season were significantly more eggs laid on the bottom southern and western aspects of the tree. The higher incidence of eggs on the southern and western aspects of the tree also suggests that during the early part of the season moths are active in that part of the tree which is the most advanced in blossom and fruit formation. A strong and uniform blossom period is mainly dependent on sufficient accumulation of Richardson's chilling units in the winter months (Matthee 1982). In the Northern Hemisphere there are few apple-producing areas that do not receive sufficient Richardson's chilling units for a short and uniform blossom period compared with apple-producing areas in the Western Cape. Therefore, the blossom of the apple tree in the Northern Hemisphere will be shorter and more uniform, and oviposition differences with respect to aspect and elevation may not be as evident as in many apple-producing areas of the Southern Hemisphere.

1.4.2 Fruit spurs and branches

1.4.2.1 Oviposition on wood

Fruiting spurs and branches were used independently to ascertain the oviposition preferences of codling moth and possible seasonal shifts in these preferences. Using fruiting spurs as sampling units, the order of preference for oviposition sites was leaves, fruit and wood with only one live egg being recorded on the wood. In the case of the branches as sampling units, leaves were the preferred oviposition site but wood, particularly at the beginning of the season on GS trees, was an important oviposition site. However, as the season progressed there was a rapid increase in the number of eggs laid on the leaves compared to the wood and fruit. Many workers have reported on the distribution of eggs on the leaves, fruit and twigs (Jenne 1909; Hall 1929; Summerland & Steiner 1943; Gayner

1949; MacLellan 1962; Garlick cited in Putman 1963; Geier 1963; Damiano 1964; Wood 1965; Audemard 1976; Jackson 1979; Hagley *et al.* 1980 and Blago & Dickler 1990). In nearly all cases the oviposition site, in order of preference, was leaves, fruit and wood, although a few studies reported eggs on the wood. Codling moth lays very few eggs on the wood of the spur. Eggs on the wood are found mostly at the base of, or between, the fruit and leaf spurs. Thus the fruit spur on its own cannot provide complete data on oviposition behaviour.

The reason for the greater number of eggs on the wood of GS branches during the first three weeks may have been that GS trees were the first to blossom and the blossoms attracted gravid females (Nel 1941; Hattingh 1942). Just before and during the initial stages of blossom there were few mature leaves present for oviposition and consequently many eggs were laid on the wood. Many of the eggs laid on actively growing leaves tended to become dislodged due to a combination of rapid leaf growth, rain and wind. The GD trees began producing blossoms and leaves up to two weeks after GS trees. A further reason why more eggs were laid on the wood of GS branches at the beginning of the season, may have been that the GS spur and fruit stalk is shorter than that of GD. Consequently the leaves and fruit of the GS spur, the preferred oviposition sites, are closer to the wood. In the case of GD trees there also appears to be more leaves present during blossom. Blago & Dickler (1990), on the basis of their results and those of Jackson (1979) and Hagley *et al.* (1980), stated that under undisturbed field conditions eggs were not laid on the wood of branches. The authors suggested that Audemard (1976) found eggs on the wood because the experiments had involved caged-in branches which could have affected oviposition activity. In experiments with caged-in branches, only limited numbers of eggs were recorded on the wood, indicating that site selection by ovipositing females may not be detrimentally influenced by caging. Although Jackson (1979) had used branches as his sampling unit he stated that these surfaces were not thoroughly searched. Hagley *et al.* (1980) only used fruit clusters, the cut end being placed in a vial of water. Therefore, not only was the greater part of the wood not available for oviposition but the conditions for oviposition were artificial. Geier (1963) and Wood (1965) whose studies were based on fruit spurs from the orchard, found no eggs on the wood. Data in the present from the spurs and branches suggest that, had previous researchers incorporated branches as a sampling unit, a more complete record of oviposition would have been obtained. However, it is possible that the distribution pattern of eggs on GS (high proportion of eggs on wood) in the early part of the season is unique to South Africa and other areas with similar climates because the moths emerge well before blossom and are not in synchrony with the host. In the more typical apple-growing climates where codling moth is in synchrony with the host, there may be little

oviposition on wood except for occassional eggs on the wood of fruit spurs.

1.4.2.2 Oviposition on leaves

Using fruit spurs as sampling units there was a significant increase in the number of eggs laid on GD leaves when compared with GS leaves. In the case of branches, there was an increase with time in the number of eggs on GD and GS leaves (Fig. 5). Although the mean ratio of eggs on the upper to lower surface of GD and GS leaves did not differ significantly, there was a seasonal change in the ratio. At the beginning of the season fewer eggs were laid on the lower surface than on the upper surface. However, during the peak oviposition period of the second and third generations more eggs were recorded on the lower surface than on the upper surface. Toward the end of the season the ratio was similar to that at the beginning of the season. No explanation can be provided for this trend. These findings are similar to those of Hall (1929) who observed that early in the season most eggs were laid on the upper leaf surface and, in midsummer, on the lower surface. However, Jackson (1979) reported a seasonal increase in the percentage of eggs on the upper leaf surface, with a corresponding decrease in eggs on the lower surface.

There was contingency between cultivar and leaf surface, with more eggs being recorded on the lower surface of GD leaves and more eggs being laid on the upper leaf surface of GS. This suggested that the lower surface was the preferred oviposition surface on GD leaves, whereas on GS leaves the top surface was preferred. The difference between the two cultivars with respect to the lower and upper leaf surfaces as oviposition sites could be due to a number of factors. Several workers have cited pubescence as a factor inhibiting oviposition on the leaf surfaces (Jackson 1979; Plourde *et al.* 1985; Hagley *et al.* 1980). Curtis *et al.* (1990) stated that the data presented by Plourde *et al.* (1985) indicated that oviposition was affected only when the level of pubescence exceeded 70 trichomes/cm^2. The level of pubescence on the lower surface of all cultivars studied exceeded 70 trichomes/cm^2.

1.4.2.3 Oviposition on fruit

Oviposition on the fruit increased throughout the season on fruiting spurs and branches. The preferred oviposition site on the fruit was the fovea of the stalk insertion and the rounded cheek area surrounding the fovea. This corresponds with the results of Blago & Dickler (1990), who observed that the preferred oviposition site on the fruit was the fovea of the stalk insertion, but differs from

those of Plourde *et al.* (1985), who found a significant preference for the middle of the fruit as compared to the stalk or calyx ends. The significantly greater number of eggs recorded on the apples of GS fruit spurs than on those of GD fruit spurs may not be a reflection of cultivar preference but due to the way the apple is attached to the fruit spur. The average length of 71 GS stalks was 1.99 cm (SE ° 0.04) while that of 73 GD stalks was 3.13 cm (SE ° 0.06). The GS apple with its shorter stalk is positioned closer to the leaves, the preferred oviposition site, than is the GD fruit and consequently more eggs are laid on GS fruit. The greater number of eggs recorded on sections 1 and 2 was probably due to the closer proximity of these sections to the leaves of the fruit spur on which most of the eggs are laid.

1.4.2.4 Fruit spurs of various fruit densities

In the present study there was a linear relationship between the number of eggs per spur and number of apples per spur. Therefore the number of fruit per spur is an important factor influencing oviposition. With the exception of spurs with one fruit, all other spur classes fitted the negative binomial distribution, indicating a clumping of the eggs within spurs with more than one fruit. Geier (1963) found that the egg distribution around individual fruit tended to randomness, as was oviposition within fruit-bearing spurs. He concluded that each fruit constituted an independent oviposition goal and each goal had an equal chance of being reached. Wood (1965), however, found that egg distribution with regard to individual fruits was not always random. He also found that distribution within fruit spurs was not always random, and concluded that the non-random distributions occurred as a result of larger population densities. Jackson (1979) found that the average number of eggs per spur and per fruit were curvilinearly related to the number of fruit per spur, suggesting that eggs were neither laid randomly with respect to fruit-bearing spurs nor individual fruits and concluded that the presence and number of fruit per cluster were important factors influencing oviposition. Distributions within spur classes fitted the negative binomial distribution. Jackson (1979) stated that the discrepancies between his data and those of Geier (1963) and Wood (1965) were possibly due to the much larger moth populations in his study trees.

Although the present studies were undertaken in an unsprayed apple orchard supporting a high moth population, the results were more similar to those of Wood (1965) than those of Jackson (1979). Although Jackson (1979) found a non-random distribution with respect to individual fruits much of the variation was due to those spurs with only one apple. Jackson (1979) referred to apples

possessing "spheres of influence" over female moths whereas Geier (1963) referred to apples as independent goals for ovipositing females. The fruit spur, consisting primarily of the fruit and leaves, is undoubtedly the target to which oviposition is directed and the greater the number of fruit per spur the greater the attraction of fruit spurs to female moths. That the fruit on the branch is the goal, and not individual spurs, is reflected by the high percentage of eggs laid within 6 cm of the fruit, over 82.9 % for GS and 62.4 % for GD. It appeared that beyond the 6 cm mark there was a rapid decline in the "sphere of influence" that Jackson (1979) referred to. Within the sphere of influence of the fruit spur the moth laid predominantly on the leaves irrespective of whether the leaf belonged to a fruit or leaf spur.

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Table 1. Number of *Cydia pomonella* eggs recorded in the top and bottom half of apple trees during the early-season (first generation moths) and late-season (second and third generation moths) in a single season.

Period	Number of eggs		
	Top half	Bottom half	Total
Early season	24	52	76
Late season	280	216	496
Total	304	268	572

Table 2. Frequency distribution of spurs bearing live, and live plus hatched *Cydia pomonella* eggs of the first and subsequent generations on Golden Delicious and Granny Smith trees during 1986.

Number of eggs	GOLDEN DELICIOUS Frequency of spurs				GRANNY SMITH Frequency of spurs			
	First generation		Second and third generations		First generation		Second and third generations	
	Live	Live plus hatched	Live	Live plus hatches	Live	Live plus hatched	Live	Live plus hatched
0	1590	1573	2216	1755	1557	1516	1456	1103
1	9	23	152	438	41	74	111	317
2	1	4	27	144	2	9	23	108
3			5	42		1	5	34
4				15			2	16
5				3			2	7
6				1			0	7
7				2			0	5
8							0	2
9							1	1
Average number of eggs/spur	0.007	0.019	0.092	0.395	0.028	0.059	0.124	0.523

Table 3. Frequency distribution of spurs bearing live, and live plus hatched *Cydia pomonella* eggs of the first and subsequent generations on Golden Delicious and Granny Smith trees during 1987.

Number of eggs	GOLDEN DELICIOUS Frequency of spurs				GRANNY SMITH Frequency of spurs			
	First generation		Second and third generations		First generation		Second and third generations	
	Live	Live plus hatched	Live	Live plus hatches	Live	Live plus hatched	Live	Live plus hatched
0	1386	1325	2297	1483	1379	1294	2372	1576
1	48	102	217	567	57	137	165	606
2	6	12	39	271	4	9	21	224
3		1	5	124				87
4			0	62				35
5			1	30				14
6			1	13				9
7				5				4
8				2				0
9				2				3
10				0				1
11				1				1
Average number of eggs/spur	0.042	0.090	0.125	0.574	0.045	0.108	0.083	0.646

Table 4. Distribution of live *Cydia pomonella* eggs on leaves, fruit and wood of spurs on Golden Delicious and Granny Smith cultivars.

Year	Cultivar	Generation	Number of eggs				
			leaves		Fruit	Wood	Total
			Upper surface	Lower surface			
1986	Golden Delicious	First	6	5	0	0	11
		Second and third	59	118	44	0	221
		Total	188		44	0	232
	Granny Smith	First	36	5	4	0	45
		Second and third	67	40	92	0	199
		Total	148		96	0	244
1987	Golden Delicious	First	15	43	2	0	60
		Second and third	85	215	20	1	321
		Total	358		22	1	381
	Granny Smith	First	47	7	11	0	65
		Second and third	95	39	79	0	213
		Total	188		90	0	278

Table 5. Distribution of live *Cydia pomonella* eggs on leaves, fruit and wood from Topred spurs in 1989 and 1990.

Year	Number of eggs				
	Leaves		Fruit	Wood	Total
	Upper surface	Lower surface			
1989	72	37	41	1	151
1990	50	56	28	2	136

Table 6. Average number of trichomes/cm^2 on the upper and lower leaf surface of three apple cultivars in November and April.

Cultivar	Trichomes/cm^2 (± S.E.)			
	November		April	
	Upper surface	Lower surface	Upper surface	Lower surface
Granny Smith	90.0 (±6.49)	1782.0 (±92.64)	14.7 (±3.92)	1015.7 (±34.89)
Golden Delicious	0.5 (±0.5)	107.3 (±6.04)	0.0 (±0.00)	73.8 (±10.56)
Topred	12.6 (±2.74)	795.3 (±27.94)	0.0 (±0.00)	949.2 (±64.21)

Table 7. Results of a split-split plot analysis of variance performed on transformed number of live eggs of *Cydia pomonella* oviposited on Granny Smith and Golden Delicious spurs.

Source	*d.f.*[1]	MS[2]	*p*[3]
Blocks (years)	1	4.3080	0.3172
Cultivar	1	0.6472	0.6059
Error (a)	1	1.2750	0.3478
Time	7	26.0383	0.0001
Cultivar x time	7	0.6936	0.8563
Error (b)	14	1.5520	0.3977
Location	1	95.4943	0.0001
Cultivar x Location	1	14.1799	0.0053
Time x Location	7	1.6344	0.3575
Cultivar x time x location	7	2.9822	0.0922
Cultivar x time x location, linear	1	15.2582	0.0041**
Cultivar x time x location, quadratic	1	1.1608	0.3679
Cultivar x time x location, cubic	1	0.5035	0.5518
Cultivar x time x location, regression	4	0.9883	0.3000
Error (c)	16	1.3625	
Total corrected	63		

[1] *d.f.* = degrees of freedom
[2] MS = mean square
[3] *p* = probability
** = highly significant

Table 8. Results of a 2 x 2 factorial analysis of variance performed on the slopes and intercepts of the linear regressions.

Source	*d.f.*[1]	MS[2]	*p*[3]
Intercepts:			
Common	1	39.6067	0.0016
Cultivar	1	2.9955	0.3649
Locations	1	15.2843	0.0437*
Cultivar x locations	1	3.1410	0.3536
Slopes:			
Common	1	49.5674	0.0005
Cultivar	1	2.3488	0.4220
Location	1	0.3464	0.7572
Cultivar x locations	1	15.2582	0.0439*
Error	56	3.5898	
Total corrected	64		

[1] *d.f.* = degrees of freedom
[2] MS = mean square
[3] *p* = probability
* = highly significant

Table 9. Distribution of live *Cydia pomonella* eggs on leaves, fruit and wood of spurs on Golden Delicious and Granny Smith cultivars.

Year	Cultivar	Generation	Number of eggs				
			leaves		Fruit	Wood	Total
			Upper surface	Lower surface			
1987	Golden Delicious	First	7	36	2	5	50
		Second and third	37	98	13	15	163
		Total	178		15	20	213
	Granny Smith	First	57	20	9	56	142
		Second and third	82	38	31	16	167
		Total	197		40	72	309
1988	Golden Delicious	First	16	44	5	3	68
		Second and third	210	471	53	32	766
		Total	741		58	35	834
	Granny Smith	First	44	24	24	28	120
		Second and third	283	218	61	49	611
		Total	569		85	77	731

Table 10. Results of the split-split plot analysis of variance performed on transformed number of live eggs of *Cydia pomonella* oviposited on Granny Smith and Golden Delicious branches.

Source	*d.f.*[1]	MS[2]	*p*[3]
Blocks (years)	1	5012.6904	0.1315
Cultivar	1	764.2648	0.3137
Error (a)	1	220.2731	
Time	6	3107.6910	0.0068
Cultivar x time	6	277.9843	0.8134
Error (b)	12	583.4893	
Location	2	18901.0842	0.0001
Cultivar x location	2	514.3217	0.1557
Time x location	12	1233.8668	0.0003**
Cultivar x time x location	12	115.7033	0.9283
Error	28	258.5461	

[1] *d.f.* = degrees of freedom
[2] MS = mean square
[3] *p* = probability
** = highly significant

Table 11. Frequency distribution of live *Cydia pomonella* eggs among spurs of various spur classes. Deviations of randomness from the expected frequencies were tested by the chi-square goodness-of-fit.

Fruit spur classes	Spurs (n)	Fruit (n)	Number of eggs	Hypothesis 1		Hypothesis 2	
				Eggs expected (E_1)	$\chi^2 = \frac{(O - E_1)^2}{E_1}$	Eggs expected (E_2)	$\chi^2 = \frac{(O - E_1)^2}{E_1}$
1	240	240	66	135.25	35.457	54.1	2.618
2	240	280	100	135.25	9.187	108.2	0.621
3	240	720	169	135.25	8.422	162.3	0.277
	240	960	206	135.25	37.010	216.4	0.500
	960	2400	541	541.0	90.076	541.0	4.016
d.f.					3		3
p				< 0.001		0.2597	

Table 12. Frequency distribution of spurs bearing different numbers of live *Cydia pomonella* eggs in four different spur classes.

No. of fruits/ spur (class)	Number of egg/spur	Observed number of spurs	Expected number of spurs (Poisson)	Chi-square	Expected number of spurs (negative binomial)	Chi-square
1	0	184	182.2973	0.0159	184.8233	0.0037
	1	49	50.1318	0.0256	45.9065	0.0085
	2	4			7.9230	1.9424
	3	3	7.5709	0.0434	1.3469	2.0289
	4	0				
	5	0				
	6	0				
	Total	240	240	0.0845	239.9997	4.1835
	d.f.			1.0		
	p			0.7713		0.0408
2	0	175	158.2178	1.7801	174.0688	0.0050
	1	40	65.9241	10.1944	44.0019	0.3640
	2	17	13.7342	0.7766	14.2148	0.5457
	3	6			4.9251	0.2346
	4	2	2.1239	16.2571	2.6467	0.1580
	5	0				
	6	0				
	Total	240	240	29.0082	239.8573	1.3073
	d.f.			2		
	p			< 0.001		0.5201

Table 12 continued:

No. of fruits/ spur (class)	Number of egg/spur	Observed number of spurs	Expected number of spurs (Poisson)	Chi-square	Expected number of spurs (negative binomial)	Chi-square
3	0	138	118.6849	3.1434	139.1217	0.0090
	1	65	83.5740	4.1280	59.9368	0.4277
	2	19	29.4250	3.6935	24.5442	1.2524
	3	10	6.9067	1.3854	9.8765	0.0015
	4	5			3.9391	0.2857
	5	2	1.4072	30.8876	2.1804	0.3081
	Total	240	239.9978	42.2379	239.5987	2.2844
	d.f.			3		3
	p			< 0.001		0.5155
4	0	115	101.7283	1.7315	114.4707	0.0024
	1	70	87.3168	3.4343	73.6030	0.1764
	2	39	37.4735	0.0622	32.8960	1.1326
	3	11	10.7216	0.0072	12.5527	0.1921
	4	2			4.3798	1.2931
	5	1	2.7521	1.8361	1.8984	0.6392
	6	2				
	Total	240	239.9923	7.0713	239.8006	3.4358
	d.f.			3		3
	p			0.0697		0.3292

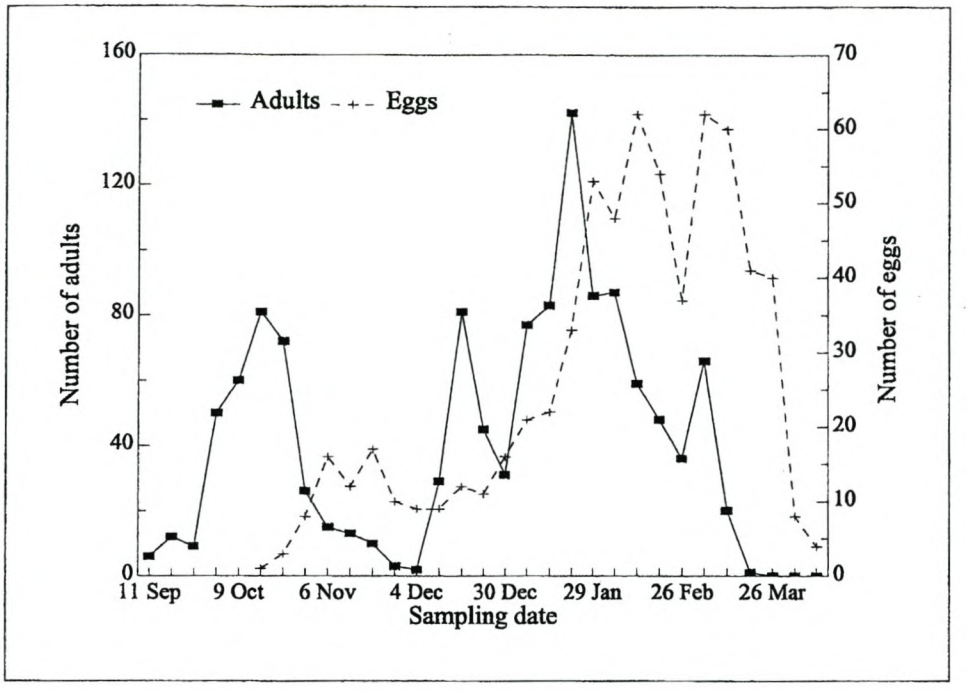

Fig. 1. Adult emergence and oviposition pattern of *Cydia pomonella* females recorded weekly in an unsprayed apple orchard during the 1985/86 fruit season.

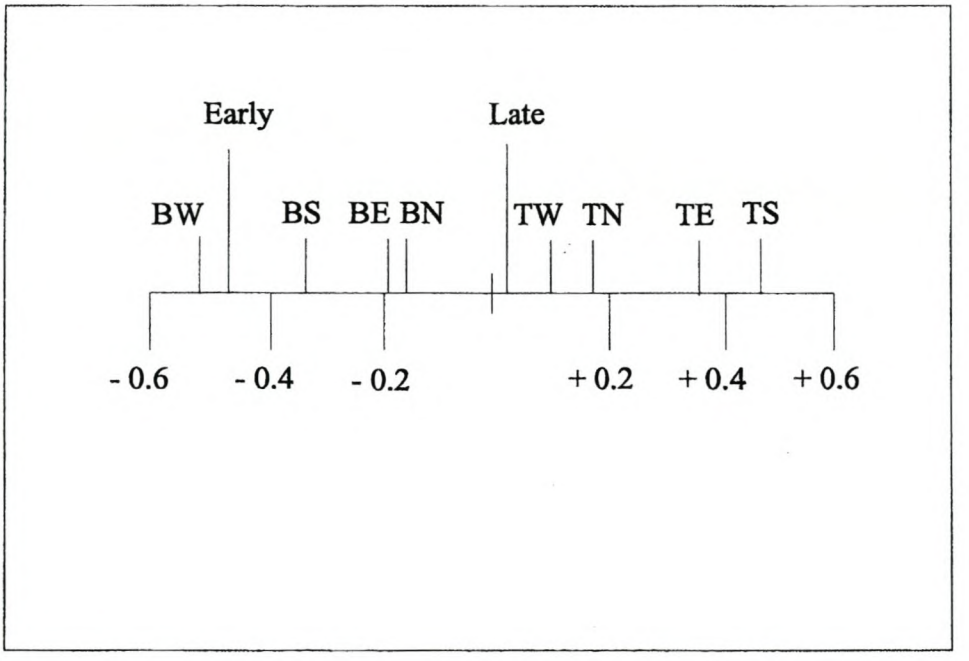

Fig. 2. Projection of the four quadrants (N, S, E, W) from the top (T) and bottom (B) of the Golden Delicious trees on the first principle axis (29.6 % of the inertia) for live eggs.

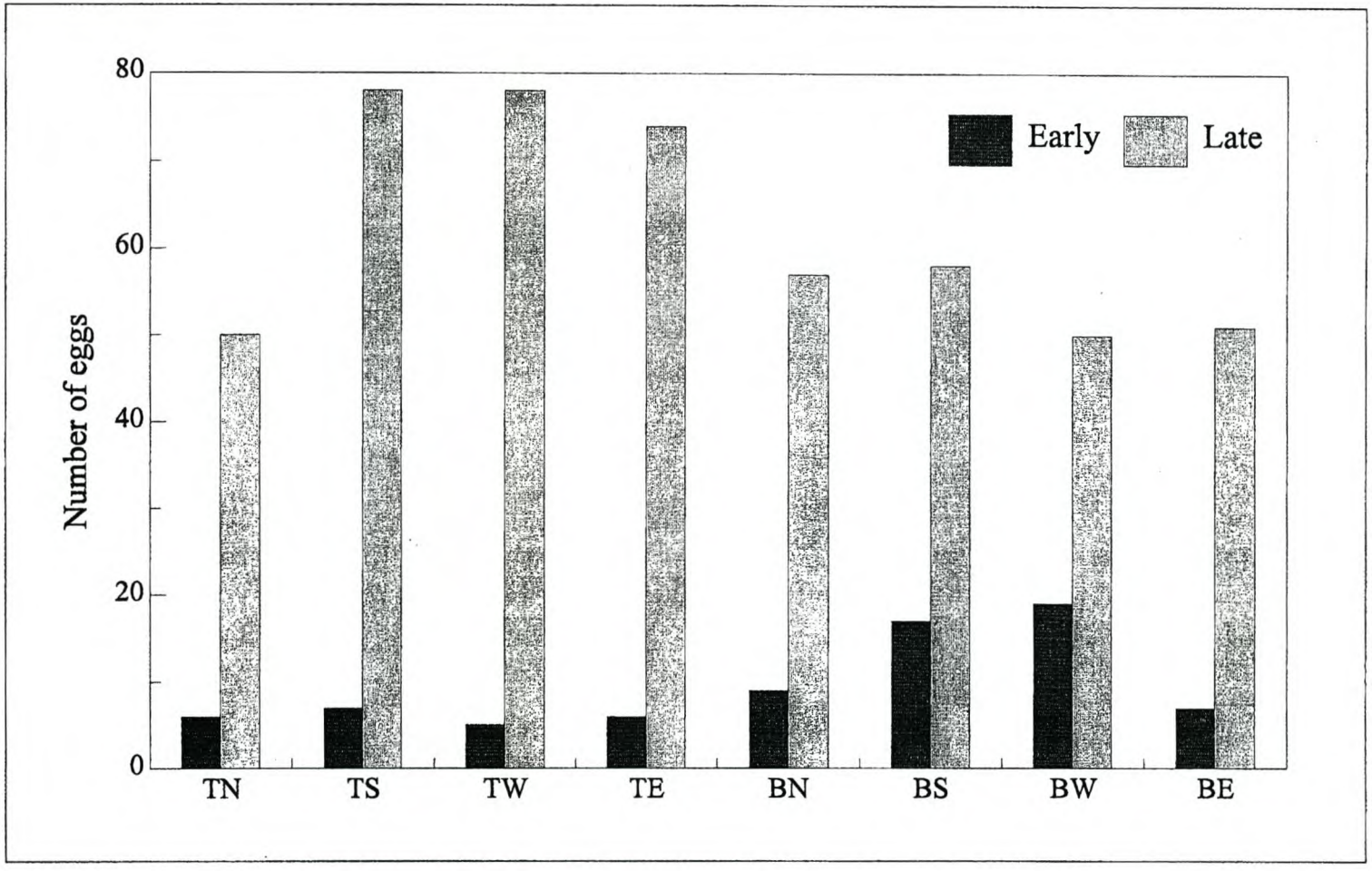

Fig. 3. Number of *Cydia pomonella* eggs recorded in the top and bottom of the four aspects of apple trees (T = top; B = bottom; N = north; S = south; W = west; E = east) during the early and late season periods.

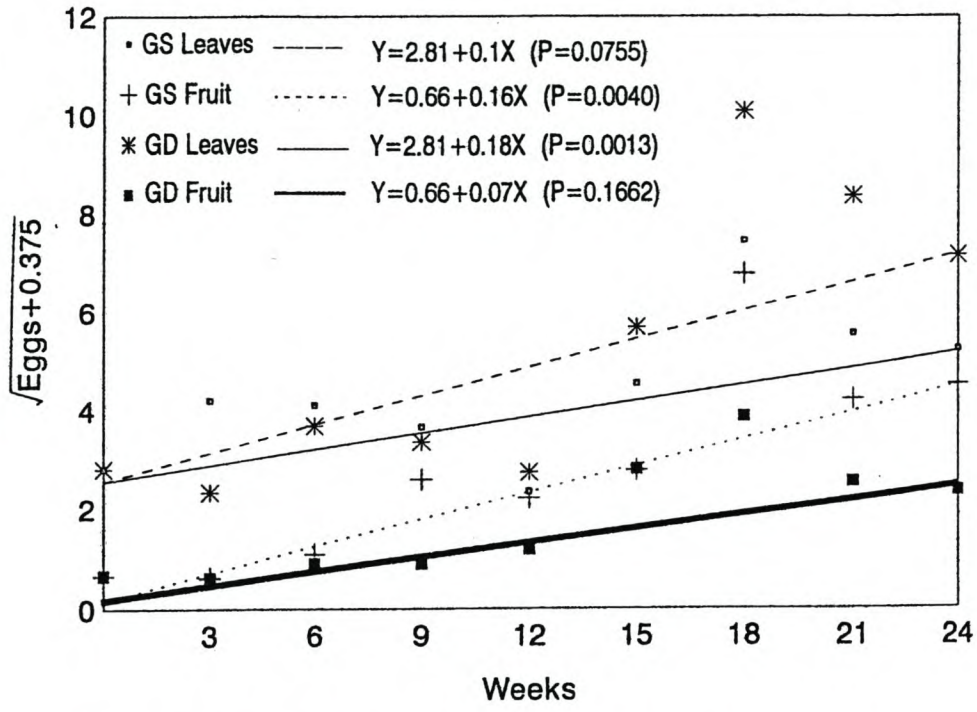

Fig. 4. Transformed number of *Cydia pomonella* moth eggs recorded on fruit spurs sampled weekly from blossom to harvest during 1986 and 1987 on Granny Smith (GS) and Golden Delicious (GD) leaves and fruit.

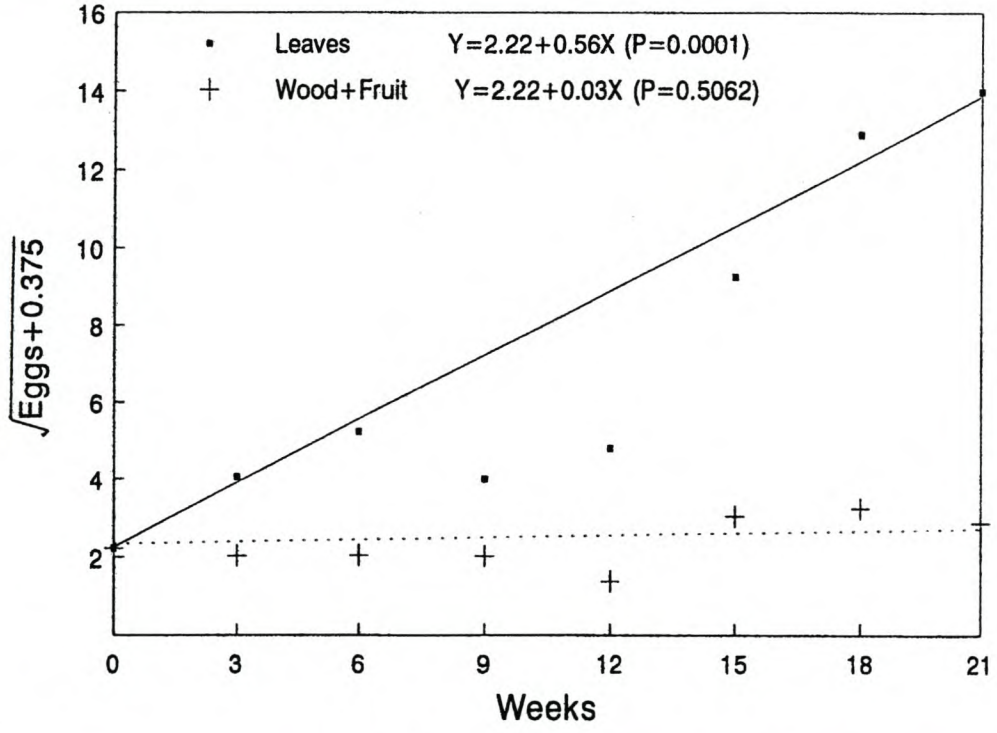

Fig. 5. Average number of *Cydia pomonella* eggs recorded on leaves, and fruit and wood from combined transformed data on Granny Smith and Golden Delicious over a period of 21 weeks.

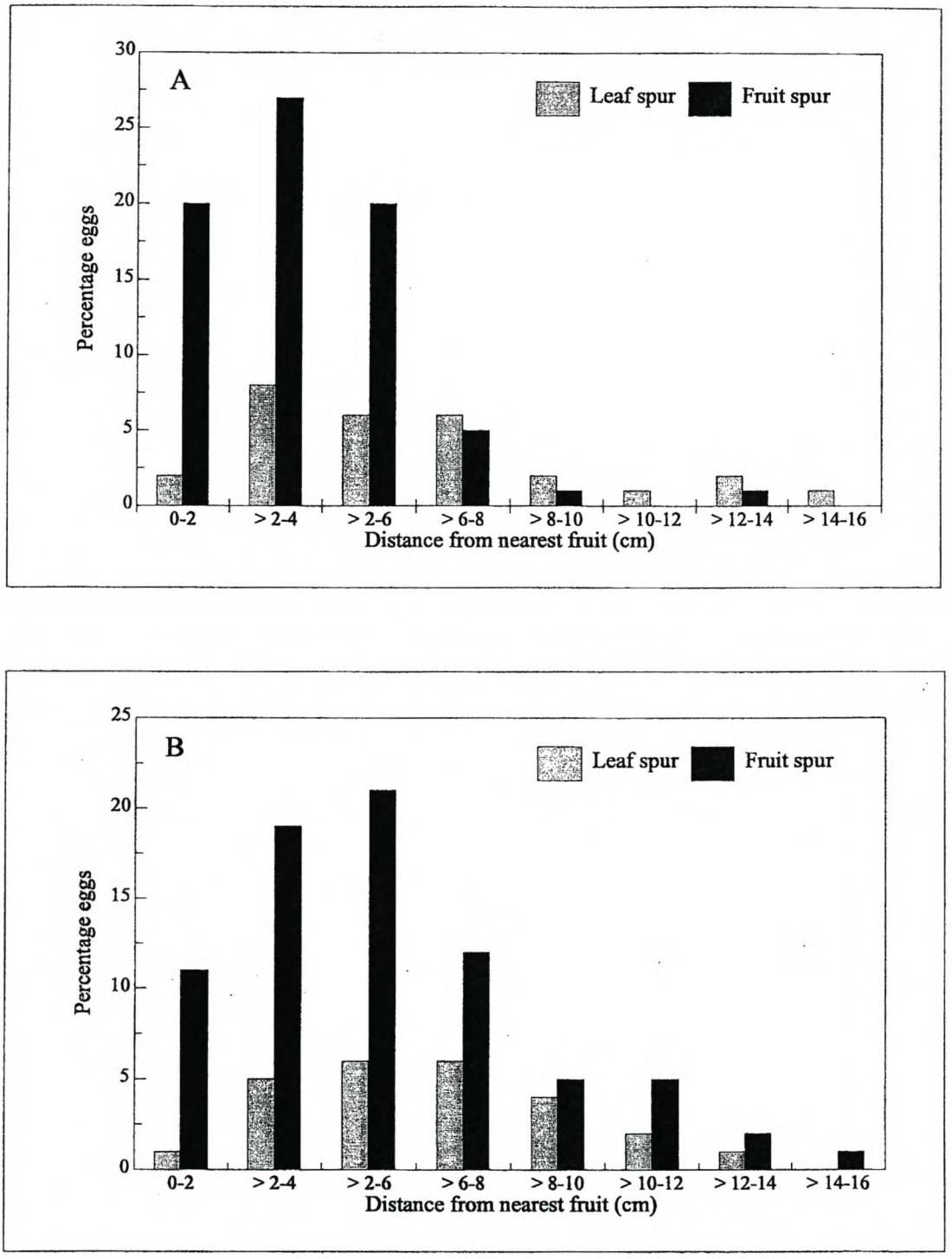

Fig. 6. Percentage distribution of *Cydia pomonella* eggs on (A) Granny Smith and (B) Golden Delicious branches at 2 cm intervals (up to 16 cm) from the nearest fruit.

2. DEVELOPMENT RATES OF THE EMBRYONIC AND IMMATURE STAGES OF CODLING MOTH AT CONSTANT AND FLUCTUATING TEMPERATURES WITH TEMPERATURE EFFECTS ON LONGEVITY, OVIPOSITION AND MATING

ABSTRACT

Development rates of the egg, larval and pupal stages of the codling moth, *Cydia pomonella* (Linnaeus), on apples were determined at constant temperatures of 15, 17, 20, 25 and 30°C ± 1°C and at fluctuating temperatures. Spring and summer adults were exposed to constant temperatures of 15, 17, 19 and 21°C and fluctuating temperatures. Throughout the range of temperatures used there was a linear relationship between rate of development and temperature for the embryonic and immature stages. The lower threshold temperatures for embryonic, larval and pupal development were 11.1, 7.9, 9.9°C respectively. The degree-days required to complete embryonic, larval and pupal development were 80.5, 345, and 279 respectively. The response of the different stages of *C. pomonella* to constant temperatures was similar to that under fluctuating temperatures. The lower threshold temperature for the preoviposition period was 11.4°C with a thermal requirement of 22.8 degree-days. Moths did not mate and few eggs were laid at temperatures below 15°C or above 27°C. Moth longevity decreased with increasing temperature. There was seasonal variation in longevity and oviposition at constant and fluctuating temperatures. Summer adults produced significantly more eggs than spring adults at constant temperatures. At constant and fluctuating temperatures there were five distinct larval instars.

2.1 INTRODUCTION

The codling moth, *Cydia pomonella* (Linnaeus) (Tortricidae), is a major pest of apples and pears and to a lesser extent stone fruits in South Africa (Petty 1925; Petty & Joubert 1926; Myburgh 1963; Myburgh *et al.* 1973; Blomefield 1989). Previous research has been directed toward determining the seasonal occurrence, oviposition behaviour and egg hatch for the improved timing of insecticide sprays for codling moth control in South African pome fruit orchards (Petty 1932; Nel 1940, 1941; Hatting 1942, 1943; Blomefield *et al.*1997). The identification of the codling moth female sex pheromone (Roelofs *et al.* 1971) made it possible to attract and trap moths. This led to the development of a monitoring system for codling moth, and the application of sprays according to a trap catch threshold (Myburgh & Madsen 1975). Despite an improvement in the management of codling moth, the continuing use and heavy reliance on insecticides, increasing concern regarding resistance, and the decreasing number of insecticides

suitable for an effective resistance management strategy have resulted in concern regarding the correct use and timing of insecticides (Blomefield 1994). The development of an integrated control programme for codling moth, based on minimum use and correct timing of insecticides, requires a thorough understanding of the biology of codling moth. As such there is an urgent need for detailed information on the biology of this pest to assist in the development and implementation of effective control programmes in South African pome fruit orchards.

Although relative humidity (Shelford 1927), food quality (Hathaway *et al.* 1971) and photoperiod (Riedl & Croft 1978) have been shown to affect the development of codling moth, temperature is considered the most important (Wilson & Barnett 1983; Higley *et al.* 1986; Kneifl 1992). The relationship between temperature and development of codling moth was first investigated in detail by Glenn (1922) using mean daily temperatures to establish the development rates of the various life stages. More recent studies have measured the development rates of codling moth under controlled temperatures (Rock & Shaffer 1983; Pitcairn *et al.* 1991). These field and laboratory studies have provided estimates of the lower threshold temperature of codling moth which vary between 10 and 12°C. Rock & Shaffer (1983) showed no decline in the development rate up to 32°C, while Pitcairn *et al.* (1991) suggested that the upper developmental thresholds for the egg and pupal stages are near 27.8°C and for the larval stage 32.2°C. Using 10°C as the lower threshold temperature the average number of degree days (°D) to complete a generation varied between 611.7 and 631.4°D (Glenn 1922; Pitcairn *et al.* 1991). Degree-day accumulations used in conjunction with pheromone trap catches are useful for predicting critical stages in a pest's development, such as egg laying, egg hatch and the seasonal phenology of the pest (Headlee 1931; Batiste *et al.* 1973; Riedl & Croft 1978; Welch *et al.* 1978; Pickel *et al.* 1986; Blago & Dickler 1990; Beers & Brunner 1992; Ahmad *et al.* 1995). Although most phenology models for codling moth use a base temperature of 10°C (Glenn 1922) as the developmental threshold for all the stages of codling moth, there are degree-day prediction models for egg hatch that use a base temperature of 11,1°C (Hagley 1973). It is possible that the threshold and degree-day estimates for the development of the embryonic and immature stages of codling moth in South Africa may differ from those obtained in other areas of the world.

Temperature has also been shown to have an effect on the longevity of adult moths, which decreases with increasing temperature (Hagley 1972). However, research has shown little variation in seasonal longevity (Selkregg & Siegler 1928; Geier 1963; Hathaway *et al.* 1971). Hagley (1972) found a correlation between longevity and fecundity and the duration of the oviposition period. The oviposition period of

codling moth was reported to be relatively short, particularly at higher temperatures, with 90% of the eggs being oviposited by the fifth day (Howell 1981). The fecundity of summer generation moths tended to be higher than that of the spring moths (Hall 1929; Deseö 1973). Codling moth mating has been reported to occur either before or after sunset (Borden 1931; Cutright 1964). However, many of the investigations on longevity, oviposition and mating have been undertaken with laboratory colonies that may differ from field populations due to adaptation to laboratory conditions (Proverbs & Newton 1962; Deseö 1971; Hagley 1972; Batiste & Olson 1973; Hathaway *et al.* 1973; Howell 1981). There are therefore inherent problems in relating laboratory observations to field observations (Geier & Briese 1978). To avoid the limitation of laboratory studies with laboratory reared moths, observations in this study were undertaken with field moths from the spring and summer generations.

The head capsule width of the larval stages of Lepidoptera species is an important parameter in identifying the instar (Beaver & Sanderson 1989; Russel & Bouzouane 1989). This is made possible by the growth of the fully sclerotised head capsule being discontinous, with most measurable changes in size occurring after each moult (Chapman 1982). The head capsule width of each instar remains relatively constant during each growth stage and can be used to differentiate larval instars (Daly 1985). The correct identification of each instar of a pest can be of practical significance in pest management. However, many factors can influence the number of instars and head capsule size. Low temperature (Guppy 1969, Russel & Bouzouane 1989) and food quality have been shown to affect the size and number of larval instars (Atkinson 1980; Scriber & Slansky 1981; Russel & Bouzouane 1989). In order to determine the reliability of head capsule measurements in identifying instars it is essential to compare the head capsule widths of laboratory individuals with the measurements of field collected larvae, preferably at different stages of crop development.

The objectives of this study were to investigate the influence of temperature on development of the embryonic and immature stages, longevity and oviposition of *C. pomonella* and compare the findings to similar studies undertaken by other researchers. Observations are also presented on mating of spring and summer moths at constant and fluctuating temperatures. The information generated from this study will hopefully provide a better understanding of codling moth biology and behaviour, and provide the means of developing a phenology model for the predicting phenological events of the insect such as first egg hatch in the field and commencement of second and third moth flights. This information would also be used to accurately schedule control measures and to pin-point the time at which damage was caused due to control failures in the field.

2.2 MATERIALS AND METHODS

Eggs, larvae and pupae used for the development rate studies were obtained from a laboratory colony. The colony was started in 1986 from fifth instar larvae collected in corrugated cardboard bands placed around the trunks of trees in an unsprayed apple orchard at the Elgin Experiment Farm, Elgin, South Western Cape (34.09S 19.02E) at an elevation of 305 m. Larvae were reared on a wheat-germ diet described by Guennelon, *et al.* (1981), at 25°C ± 3°C, a continuous low intensity illumination and 50% ± 10% relative humidity (RH). The moths and pupae were reared at 22°C ± 3°C, a photoperiod of 16:8 (L:D) and a RH of 70 ± 10%. Moths used for the oviposition and mating studies were obtained from the unsprayed apple orchard on the Elgin Experiment Farm. Spring generation moths (early September to late November) originated from fifth instar larvae collected weekly from corrugated cardboard bands placed around the trunk and branches of Granny Smith trees the previous season. The diapausing larvae were kept in two cylindrical gauze cages suspended from branches in the orchard throughout the summer and winter months. The summer generation moths originated from mature larvae leaving the fruit in December through to February.

2.2.1 Effects of temperature on development

2.2.1.1 Egg stage

Egg development was observed at constant temperatures of 15°C, 17°C, 20°C, 25°C and 30°C ± 1,0°C, in incubators with a 16:8 (L:D) photoperiod. The eggs were held in desiccators in which the RH was maintained at 70% using a potassium hydroxide solution, following the method of Solomon (1951). Eggs of 3 to 5-day old moths, laid on wax paper during a half-hour period, were used. The wax paper was cut into 3 cm strips bearing a known number of eggs. The paper was attached to a circular wire gauze cage which was placed in the desiccator. Observations at each temperature were replicated four times and the number of eggs in each replicate varied from 60 to 250. Eggs were observed daily until the black-head stage of development and thereafter three times a day until egg hatch. With the commencement of egg hatch eggs were observed every one to two hours during the light period. The laboratories in which the incubators were held were maintained at a similar temperature and humidity.

To determine the effect of fluctuating temperatures on egg development, the duration of the egg stage was also observed outdoors in an insectary. At regular intervals, mostly weekly from October to March, a

group of eggs was collected using the same method described previously and placed in an insectary. To reduce the effects of desiccation, particularly during the hot summer months, the eggs were placed in a circular plastic container (21 x 11 cm) filled with water to a depth of 3 to 4 cm. The wax paper on which the eggs were laid was placed on a plastic platform suspended above the water 5 cm from the top of the container. The method of observation was the same as that for constant temperatures. Daily maximum and minimum temperatures from a weather station about 100 m from the insectary were used to calculate the mean temperature for each incubation period.

2.2.1.2 Larval stage

Larval development was observed at constant temperatures of 15°C, 17°C, 20°C, 25°C, and 30°C ± 1,0°C in a growth chamber with a 16:8 (L:D) photoperiod and at a relative humidity of 70% ± 5%. The observations at each temperature were replicated five times and each replicate consisted of larvae on 50 Granny Smith apples. Each apple was washed in warm water, air dried and placed in a 550 ml plastic container. Eggs collected from 3 to 5-day old moths, were maintained at 25°C ± 1°C and 70% ± 5% RH. On eclosion from the egg the neonate larvae were transferred individually with a fine brush to an apple. Depending on the size of the apple the number of larvae per apple varied from 2 to 3 individuals. The top of the container was covered with a fine gauze cloth. To provide cocooning sites for the mature larvae leaving the apples a strip of single-faced corrugated cardboard was placed in each container. All the containers and cardboard were inspected daily. On finding a cocoon the date was recorded and the larva placed individually in a glass vial sealed with cotton wool. The glass vials were inspected daily until moth emergence and the sex of the moth was recorded.

The duration of the larval stage was also observed at fluctuating temperatures in an open insectary. At fortnightly intervals, from November to March, neonate larvae were placed on 50 Granny Smith apples. The method used to transfer the larvae, observation and recording of cocoon formation and adult eclosion was the same as that used at constant temperature.

2.2.1.3 Pupal stage

Pupal development was also observed at constant temperatures of 15°C, 17°C, 20°C, 25°C, and 30°C ± 1,0°C in a growth chamber with a 16:8 (L:D) photoperiod and at a relative humidity of 70% ± 5%. Observations at each temperature were replicated eight times. Each replicate consisted of a minimum of

20 individuals.

To obtain cocoons mature apples were placed in four trays 740 x 510 x 200 mm in a breeding room at 22°C ± 3°C and 70% ± 10% and each apple was artificially infested with three neonate larvae. Strips of single faced corrugated cardboard were placed on the top of the apples and along the inside of the containers. Each container was sealed with a plastic screened lid. The cardboard strips were inspected daily between 08h00 and 09h00 and between 15h00 and 16h00. To obtain cocoons of a similar age the cocoons collected between 15h00 and 16h00 were discarded . The cocoons were placed in 300 ml containers sealed with screened lids to allow air flow. The containers were inspected daily for moth emergence.

The duration of the pupal stage was also observed at fluctuating temperatures in an open insectary. Larvae were reared on artificial medium in clear plastic containers that were kept in the insectary. Every 10 to 14 days from 2 December 1988 to 21 February 1989 larvae which had emerged the previous night from the artificial rearing medium, and spun cocoons in corrugated cardboard stuck to the sides of the plastic containers, were collected. The cocoons were placed in 300 ml plastic containers covered with a fine gauze cloth. The containers were inspected daily for moth emergence and the sex of each moth recorded.

2.2.1.4 Adult stage

The preoviposition, longevity and oviposition of the spring and summer generation moths were observed at constant temperatures of 15°C, 17°C, 19°C and 21°C ± 1°C and at a RH of 70%. The aspects of oviposition that were studied were oviposition period, days from mating to peak, 50 % and 80 % oviposition. The observations at each temperature consisted of 13 replicates, except the spring generation moths maintained at 15°C, where only eight replications were used. Newly emerged virgin moth pairs were each placed in a cylindrical nylon mesh cage (80 mm x 90 mm) with a mesh diameter of 2 mm (Fig 1). The top and bottom of each container was open. Rigidity was obtained by glueing the nylon at the top and bottom of the cage to thin circular plastic bands 6 mm in width, the top and bottom bands being attached to each other by two 6 mm plastic strips. Black velcro material was used to discourage moths from ovipositing on the plastic. The bottom of the cage was placed on wax paper and the top covered with wax paper pressed down with a clear plastic lid. A wad of cotton wool, moistened twice daily with water, was pressed against the side of each container. The cages were placed in desiccators in which a

relative humidity of 70% was obtained using a potassium hydroxide solution, following the method of Solomon (1951). The desiccators were placed in incubators which were fitted with an outer metal and inner glass door. The laboratories in which the incubators were kept had one double-layered glass wall. By positioning the incubators facing the glass wall with the outer metal door of the incubator open and the inner glass door closed, the moths were exposed to natural light and dark fluctuations. The laboratories were maintained at a similar temperature and humidity to ensure minimum disruption in temperature and humidity when the desiccators were opened and the eggs inspected.

Considerable difficulty was experienced in obtaining sufficient successful matings in the desiccators, particularly at 15°C. To overcome this difficulty moths that emerged during the day were placed in nylon net cages (30 cm x 30 cm) in each of the laboratories in which the incubators were kept. On mating and while still in copula each mating pair was gently coaxed into a test tube (150 x 12.5 mm). Immediately after separating the mated pair was carefully transferred to an oviposition cage in the desiccators. The wax paper was changed daily between 08:00 and 09:00 and kept in a laboratory at 22°C ± 3°C and RH OF 70% ±10 %.

Longevity and oviposition of the spring and summer generation moths were also observed at fluctuating temperatures in an open insectary. Between 18 October and 26 October 1988, 5 and 8 pairs of moths respectively that had mated on the same evening, were kept in cages as described for constant temperature conditions. The longevity and oviposition of 17 individual moths that had mated on different evenings between the 3 October and 16 October were also observed. Similarly, during the summer months between 24 January and 19 February 1989, 8 to 13 pairs of moths that had mated on the same evening on each occasion were also observed. The time of day when oviposition occurred was observed by hourly replacement of the wax paper after commencement of oviposition. A wad of cotton wool, moistened twice daily with water, was pressed against the side of each container.

2.2.2 Effects of temperature on fecundity

2.2.2.1 Eggs per female

The data generated from the studies on the adult stage was used to determine the number of eggs produced per female at constant and fluctuating temperatures.

2.2.2.2 Eggs per day

The data generated from the studies on the adult stage was used to determine the number of eggs produced per female at constant and fluctuating temperatures.

2.2.3 Mating

Mating was observed at fluctuating temperatures on a pear tree. Ten branches approximately 50 cm in length were each enclosed in a nylon bag with a mesh diameter of 2 mm. A pair of adults that had emerged during the day was released into each bag and observed at 5 to 10 minute intervals, until the temperature dropped below 15°C. The time of day and temperature at which mating took place was recorded. Thirty-five moths were observed mating between 1 October 1988 and 30 October 1988 and 25 moths between 10 November 1988 and 23 November 1988.

2.2.4 Head capsule width

Larvae were reared on mature Granny Smith apples at 25°C ± 1°C with a 16:8 (L:D) photoperiod and a 50% ± 5% RH. The larvae were obtained from eggs laid on wax paper during a half-hour period. Fifty neonate larvae were placed singly on an apple with a fine brush. Two days later the apples were Inspected with daily inspections taking place until the head capsule was discarded. After being discarded the head capsule was measured. This process was repeated for each instar. Apples in a poor condition were replaced with fresh apples. Measurements were made at the greatest width of the head capsule using an ocular micrometer fitted to a binocular microscope.

Head capsule measurements were also made on larvae removed from apples that had been previously infested with neonate larvae in the unsprayed apple orchard on the Elgin Experiment Farm. Shortly after Golden Delicious trees had reached full bloom, 50 branches, approximately 50 cm to 1 m in length, were enclosed in gauze-sleeve cages. Apples and leaves in the vicinity of the sleeve-cages were removed to reduce the possibility of oviposition in close proximity to the cages. Three weeks later the apples and inside of the cages were inspected, and any infested apples were removed. On 29 November 1988, the apples of 25 bags were infested with neonate larvae. On 5 December 3 infested apples were removed from each sleeve-cage and thereafter apples were removed at three to four day intervals. On each occasion 50 larvae were randomly removed from the apples, decapitated and the head capsule measured

as described previously. The experiment was repeated on 2 February 1989, the first fruit being removed on 4 February and every two to three days thereafter.

2.2.5 Pupal weights

Male and female pupae from the spring and summer periods were weighed on an analytical balance calibrated to four decimal points. The summer period was divided into an early period (December and January) and a late period (February and March). The spring pupae originated from diapausing fifth instar larvae collected weekly from corrugated cardboard bands placed around the trunk and branches of Granny Smith trees the previous season. The diapausing larvae were kept in gauze cages suspended from branches in the orchard throughout the summer and winter months. The summer generation pupae originated from mature larvae leaving the fruit in December through to end-February.

2.2.6 Statistical analysis

The lower threshold temperature for development of the embryonic and immature of codling moth as well as the preoviposition, longevity, oviposition period and number of days from mating to peak, 50 % and 80 % oviposition of the spring and summer moths was estimated by linear regression using the model $1/y = a + bx$, where x = temperature, y = time in days required to complete development, and a and b are regression constants. The number of eggs per female and daily oviposition (eggs/day) was estimated by linear regression ($y = a + bx$). The threshold temperature for development was obtained by solving for x in $1/y = 0 = a + bx$ (Arnold 1959). The thermal constant for development was calculated as the reciprocal of the slope of each regression equation. The thermal constant was compared with observed estimates of average number of degree-days required for development at constant and fluctuating temperatures. The number of degree-days required to complete development was calculated using the sin-wave model (case 3) of Baskerville & Emin (1969), based on daily maximum and minimum temperatures.

Intercepts and slopes for longevity and oviposition (dependant variables) of moths of the spring and summer generations for constant temperatures (independant variables) were compared using standard deviations. The means of longevity and oviposition of moths of the spring and summer generations for fluctuating temperatures were compared using pairwise t-tests at the 5 % significant level. Data on pupal weights were analysed using a 3 x 2 factorial model with 3 periods (spring, early summer and late summer)

and 2 sexes (female and male) as main effects.

In order to obtain an estimate of the number of instars, histograms of head capsule size for November/December and February/March were constructed. Finite mixture analyses were then performed on the two datasets (Flury, 1995). Finite mixture analysis places each larva into one of the known subgroups (instars 1 to 5) and estimates the probability that the larva will fit into the correct subgroup. This method was preferred to that of cluster analysis. In cluster analysis the number of subgroups is determined by the analysis, but no probabilities are given regarding the allocation of individuals to a particular subgroup.

2.3 RESULTS

2.3.1 Effects of temperature on development

2.3.1.1 Egg stage

The development rates and degree-day requirements for development at the five constant temperatures are given in Table 1. The number of days required for egg hatch decreased as temperature increased, the means ranging from 19.39 days at 15°C to a mean of 4.23 days at 30°C. The lower threshold temperature for embryonic development was 11.06 and the overall degree-day estimate for development, 80.5°D, is comparable with the mean degree-day values at each temperature given in Table 1. There was a strong positive linear relationship between the reciprocal of the duration of the egg stage and temperature (Fig.2). At fluctuating temperatures between 14.8 °C and 17.09°C the observed period for egg hatch was shorter than the estimated (Table 2). However, at an ambient temperature between 19.26°C and 27.46°C the difference between the estimated and observed incubation period was 7°D. The variation between the estimated and the observed incubation period at the lower temperatures is probably a reflection of the nonlinear relationship between temperature and rate of development at the lower temperatures (Higley *et al.* 1986; Pitcairn *et al.* 1991) although a linear model is used for determining the estimate. The overall degree-day estimate for development is within 14°D of the means for fluctuating temperatures, shown in Table 2. At all constant temperatures a sharp increase in egg hatch was observed one to two hours after commencement of the light phase.

2.3.1.2 Larval stage

The duration of larval development declined from 48.94 days at 15°C to 15.46 days at 30°C respectively (Table 1). Males and females required approximately an equal number of days to complete development (Table 3) and for this reason male and female data were pooled when determining the degree-day requirements for the larval stage. The estimated lower threshold temperature for larval development was 7.9°C and the overall degree-day estimate for development was 345°D, which is comparable with the mean degree-day values at each temperature tested (Table 1). There was a strong positive linear relationship between the reciprocal of the duration of the larval stage and temperature (Fig.2). At varying temperatures the difference between the observed and estimated larval development was mostly less than 2 days or 45°D (Table 2). Male and female development rates under fluctuating temperatures were also very similar (Table 4).

2.3.1.3 Pupal stage

The duration of pupal development ranged from 56.25 days at 15°C to 13.78 days at 30°C (Table 1). The lower threshold temperature for pupal development was 9.9°C (Fig. 2) and the overall degree-day estimate for development was 279°D (Table 1). The mean degree-day accumulations at each temperature tested were comparable with the overall degree-day estimate differing by 9°D. There was a strong positive linear relationship between the reciprocal of the duration of the larval stage and temperature (Fig. 2). Males and female development rates were also very similar (Table 3). At fluctuating temperatures the observed and estimated development rates were very similar, differing by 12°D (Table 2). Male and female development rates were also very similar (Table 4).

2.3.1.4 Adult stage

2.3.1.4.1 Preoviposition period

The preoviposition development time ranged from 7.54 days at 15°C to 2.54 days at 21°C (Table 1). The estimated lower threshold temperature was 11.4°C and the overall degree-day estimate for preoviposition (22.8°D) is comparable with the mean degree-day values given at each temperature given in Table 1. Although there was a linear relationship between the reciprocal of the duration of the preoviposition stage and temperature, only 50 % of the variability in rates could be explained by changes in temperature ($P <$

0.05)(Fig 2).

2.3.1.4.2 Longevity

Details of the longevity of males and females of *C. pomonella* of the spring and summer generations are given in Fig. 4A. There were no differences between either the slopes or intercepts for male and female moths of the spring and summer generations. The intercepts and slopes of male and female moths of the seasonal generations were therefore combined. The estimated mean longevity at 15, 17, 19 and 21°C was 35.4, 23.4, 19.0 and 17.1 days. Longevity at 21°C was slightly more than half of that at 15°C.

There was a positive relationship between the reciprocal of the adult longevity and temperature (r^2 = 0.81). This suggests that longevity would be shortened by summer temperatures in the orchard. The longest recorded life span of 51 days was that of a male moth of the summer generation at 15°C, while that of a female moth was 49 days at 15°C from the spring generation.

At fluctuating temperatures moths lived from as little as three days up to 39 days (Table 5). There was a significant difference ($t_{40} = 2.867$, $P = 0.007$) in the longevity between males and females of the spring generation, females living longer than males. No difference was found in the longevity between the two sexes of the summer generation ($t_{40} = 0.375$, $P = 0.710$). Males of the spring generation lived significantly longer than males ($t_{40} = 3.684$, $P = 0.001$) and females ($t_{40} = 3.979$, $P = 0.003$) of the summer generation. Similarly females of the spring generation lived significantly longer than males ($t_{40} = 6.486$, $P < 0.001$) and females ($t_{40} = 7.280$, $P < 0.001$) of the summer generation.

2.3.1.4.3 Oviposition period

Oviposition by females of the spring and summer generations at constant temperatures is shown in Figs 4-9. There was no difference between the intercepts and slopes for the duration of the oviposition period of moths of the spring and summer generations (Fig. 4B). The intercepts and slopes for the oviposition of spring and summer moths were therefore combined. The estimated mean duration of the oviposition period at 15, 17, 19 and 21°C was 20.6, 14.7, 9.6 and 10.6 days respectively. The oviposition period at 21°C was almost half of that at 15°C. The longest oviposition period for a moth of the spring generation was 30 days at 15°C, while that for a moth of the summer generation was 40 days at 15°C.

At fluctuating temperatures the duration of the oviposition period of spring moths (11.7 days) was significantly longer than that of the summer moths (7.4 days) (Table 5) ($t_{40} = 3.416, P = 0.001$). Despite the short oviposition periods there were females of both the spring and summer generations whose oviposition period extended beyond 20 days.

2.3.1.4.4 Time to peak, 50% and 80% oviposition

There were no differences between either the intercepts or slopes for the seasonal generations in the number of days to peak oviposition (Fig.7). Consequently the intercepts and slopes for the daily oviposition rate of spring and summer moths were combined. The estimated mean number of days to peak oviposition at 15, 17, 19 and 21°C were 13.3, 6.2, 5.1 and 4.1 days respectively. There was a strong positive relationship between the reciprocal of the time to peak oviposition and temperature ($r^2 = 0.89$). This suggests that peak oviposition would be enhanced by the summer temperature conditions in pome fruit orchards. The number of days from mating to peak oviposition at 21°C was more than three times less than that at 15°C.

There were no differences between either the intercepts and slopes in the inverse mean number of days to 50 % oviposition for spring and summer moths (Table 6). The estimated mean number of days to 50 % oviposition at 15, 17, 19 and 21°C were 15.3, 7.5, 6.9 and 5.2 days respectively. The number of days from mating to 50 % oviposition at 21°C was also almost a third of that at 15°C. There was a strong positive relationship between the reciprocal to 50 % oviposition and temperature.

There were no differences between either the interceps and slopes in the inverse mean number of days to 80 % oviposition for spring and summer moths (Table 6). The mean number of days to 80 % oviposition at 15, 17, 19 and 21°C were 22.2, 11.7, 9.5 and 8.1 days respectively. The number of days from mating to 80 % oviposition at 15°C was 2.7 times more than that at 21°C. There was a strong positive relationship between the reciprocal to 80 % oviposition and temperature.

There were no differences between the slopes in the inverse mean number of days to 50 % and 80 % oviposition for spring and summer moths (Table 6)

At fluctuating temperatures there were significant differences between generations in the mean number of days at which peak ($t_{40} = 4.712, P < 0.001$), 50% ($t_{40} = 5.187, P < 0.001$) and 80% ($t_{40} = 5.627$, P

< 0.001) oviposition occurred. The number of days at which peak, 50% and 80% oviposition occurred for the summer generations was approximately half that of the spring moths (Table 5).

In two oviposition trials conducted on 18 and 26 October 1988, oviposition commenced from 1 to 4 days after mating. Oviposition was erratic due to fluctuating temperature conditions, oviposition occurring at temperatures above 15°C (Figs 8). On those afternoons and early evenings when the temperature dropped to or below 15°C very few eggs were recorded. Of the total eggs (3 409) produced by spring moths under fluctuating temperature conditions between 3/10/1988 and 18/11/88 only 4 (0,1%) were laid below 15°C (Fig. 9A). Oviposition commenced from 14h00 and stopped at 23h00 with peak oviposition occurring at 17h00 (Fig.10A).

In the oviposition trial commencing on 18 November 1988 (Fig.8) the temperature remained above 20°C for the first 21 days of the oviposition period resulting in a daily oviposition rate very similar to that obtained for the oviposition trials undertaken during the summer months (Fig.11).

In the four oviposition trials conducted between 24 January and 12 February 1989 peak oviposition occurred on the first night following mating on three occasions following mating (Fig. 11). In all trials 50% of the eggs were laid within 3 to 4 days after mating and 80% of the eggs within 4 to 9 days of mating. In these trials the temperature between 16h00 and 24h00 (Fig.11) never dropped below 15°C, with few eggs being recorded below 18°C (Fig. 9B). Although oviposition occurred at temperatures above 30°C only 0.9% of eggs were laid above 30°C, with oviposition decreasing sharply at temperatures above 27°C (Fig 9B). Oviposition commenced from 16h00 with most eggs being laid between 18h00 and 22h00 (Fig. 10B)

2.3.2 Effects of temperature on fecundity

2.3.2.1 Eggs per female

There were significant differences between the intercepts or slopes for the number of eggs produced per female (P < 0,001) for spring and summer moths (Fig. 5B). Significantly more eggs were produced per female for summer moths than for the spring moths. There was also a significant increase in the number of eggs per female for spring and summer moths as temperature increased. The estimated mean number of eggs produced per female for summer moths at 15, 17, 19, and 21°C were 153.1, 149.4, 163.3 and

188.1 respectively, while that for spring moths was 71.8, 80.2, 105.6 and 105.8 at the same temperatures. The most number of eggs (308) were laid by a female from the summer generation at a constant temperature of 21°C, whilst the most number of eggs produced by a female from the spring generation was 226 at 19°C.

At fluctuating temperatures there was no significant difference between the number of eggs for spring moths (92.6 eggs/female) and that for summer moths (121.2 eggs/female) ($t_{40} = 1.775$, $P = 0.084$) (Table 5). This was probably due to the wide variation in the number of eggs laid per female and the high summer temperatures. The most eggs produced (303) was by a female moth of the summer generation.

2.3.2.2 Eggs per day

There were also no differences between either intercepts or slopes for the daily oviposition rate of spring and summer generation moths (Fig. 5A). Consequently the intercepts and slopes for the daily oviposition rate of spring and summer moths were combined. The mean daily oviposition at 15, 17, 19 and 21°C was 6.4, 8.3, 14.8 and 14.2 days respectively. Although the mean daily oviposition at 21°C was 14.2 eggs the most eggs laid in an evening (90) was by a female from the summer generation at 19°C. The most eggs produced in an evening by a female moth from the spring generation was 68 at 21°C. For the summer generation moths maintained at 15°C periods of oviposition were frequently followed by intervals when no oviposition occurred (Fig. 6). At this temperature no oviposition occurred on 41.6 % of the days, while at 17°C, 19°C and 21°C the percentage of days when no oviposition occurred was 26.8, 11.6 and 11.0 respectively. It would appear that with increasing temperature there was a decrease in the number of days when no oviposition occurred (Fig.6). This observation was not as evident for the spring moths. Moths maintained at 15°C (34.3 %), 17°C (28.8 %) and 21°C (30.6 %) all had a similar percentage of days when egg deposition did not occur. Only at 19°C (6.1%) were fewer days observed when no egg laying took place.

At fluctuating temperatures the mean daily oviposition of summer moths (16.5 eggs/day) was significantly higher than that of the spring moths (7.7 eggs/day)($t_{293} = 7.246$, $P < 0.001$) (Table 5). The maximum number of eggs produced by a female of the summer generations in a single evening was 111, while that for a female of the spring generation was 72. The number of evenings during which more than 24 eggs were laid by a single female was greater for the summer generation (25.6%) than the spring generation (8.1%). During the spring period there were more evenings when no oviposition occurred (38.3%)

compared to the summer period (11.0%).

2.3.3 Mating

The time of day and temperature at which mating took place are presented in Figs 13 -14. The earliest mating of spring generation moths observed during September and October took place at 16:45 with most of the matings occurring between 18:00 and 19:00 (68.6%) (Fig 13A). No matings took place below 15°C, female moth activity noticeably decreasing below 16°C. Although females were inactive below 15°C males still tried to mate with females. Most matings occurred between 16°C and 19°C (Fig 14A). During November mating commenced and ended at a similar time of the day as was the case during October. Mating took place between 17:00 and 21:00 with most matings taking place between 19:00 and 20:00 (Fig 13B). Matings took place at higher temperatures during November than during October with most matings taking place between 21°C and 22°C (Fig.14B).

2.3.4 Head capsule widths

The head capsule widths and ratio of increase between the instars reared in the laboratory at 25°C are given in Table 7. It is apparent from the head capsule widths that there are five distinct larval instars as there was no overlapping of the ranges of successive instars. The ratio of increase in head capsule width between successive instars was constant. By taking the effective minimum and maximum of a normal distribution to be $\mu - 3\sigma$ and $\mu + 3\sigma$ respectively it is possible to establish the minimum and maximum range for each subgroup. By subtracting 3 x SD from the $\bar{X}_i$ to obtain the minimum and by adding 3 x SD to $\bar{X}_i$ (where $\bar{X}_i$ is the average head capsule width of instar i) to obtain the maximum, the difference between the maximum and minimum would give the range for each larval instar. The development rate in days and degree-days above the theoretical lower threshold temperature of 7.9°C for each instar was very similar at 25°C (Table 8). Males developed marginally faster than females. For comparative purposes the degree-days above the internationally used lower threshold temperature of 10°C was also included. At 25°C there was a difference of 53.5 and 37.6 °D for males and females respectively.

The head capsule widths estimated using finite mixture analysis and the ratio of increase between instars for the larvae recovered from the fruit removed from the sleeve-caged branches in the unsprayed apple orchard on the Elgin Experiment Farm are shown in Tables 9 and 10 and their frequency distributions are shown in Fig. 3A and 3B respectively. In both sets of data the ratio of increase in head capsule width

between successive larval instars was constant Tables 9 and 10. It is evident that under fluctuating temperature conditions there were also five distinct larval instars (Fig. 3A and 3B). Despite the difference in fruit maturity between December and February and the time of the year there was a very close similarity in head capsule widths between the two periods. However, the mean head capsule widths of the first (P = 0.0007), third (P = 0.0016) and fifth (P = 0.0319) instars differed between the two data sets.

The intervals at which the larvae were removed from the fruit collected from the sleeve-caged branches in the unsprayed orchard on the Elgin Experiment Farm are expressed in days and degree-days above the theoretical lower threshold temperature of 7.9°C (Tables 11-12). On each sample date the number of larval instars present varied from 1 to 3 with only one to two instars being predominate on each assessment date. Although the sample intervals were not the same, making direct comparisons difficult, the accumulated degree-days for the predominant instar on each sample date was similar and compared favourably to the studies done at constant and fluctuating temperatures. The appearance of the 5th larval instar in the December and February periods occurred after 252.1 and 248.9°D respectively.

2.3.5 Pupal weights

Details of pupal weights of the spring and summer periods are given in Fig.12. There were significant interactions between periods and sex (P = 0.006). The interactions were caused by differences in weight between female and male pupae of the spring and early and late summer periods. Female pupae were heavier than male pupae within periods (P =0.0001) and between periods (P = 0.0001). Female pupae of the early summer and late summer periods were heavier than female pupae of the spring period (P = 0.0001). However, there were no differences in weight between female pupae of the early and late summer periods (P = 0.741). Male pupae of the spring period were significantly heavier than male pupae of the early summer period (P = 0.0006) but not male pupae of the summer period (P = 0.550).

2.4 DISCUSSION

2.4.1 Development rates

The relationships between temperature and the development rate of codling moth eggs, larvae and pupae were strongly linear in the range of temperatures tested. The marked increase in the development time at 15°C indicated that this and lower temperatures fall in the unfavourable range for codling moth

development. Estimates of the lower threshold temperature for the egg, larval, and pupal development were 11.06°C, 7.89°C, 9.89°C respectively, suggesting that the egg stage is more sensitive to low temperatures than either the larval or pupal stage. Estimates of the lower threshold temperatures obtained for egg and pupal development are comparable to those of Glenn (1922) who concluded from thermal summations under varying temperature conditions that the lower threshold temperature for the egg and larva was approximately 10°C while that for the pupa was 11°C. However, he suggested that the lower threshold temperature for the egg may be greater than 10°C. Hagley (1972) reported a lower threshold temperature of 11°C ± 1°C for the egg stage. Pitcairn *et al.* (1991) found that the estimates of the lower threshold temperature for the egg, larva and pupa were 10.56, 11.54 and 12.49 respectively, suggesting that the larval and pupal stages, and not the egg stage as in the present study, were the most sensitive stages to low temperatures. Pitcairn *et al.* (1991) noted an increase in embryogenesis time above 27.8°C and concluded that 27.8°C is close to the upper threshold of the egg stage. Rock & Shaffer (1983) who studied developmental times from neonate larvae to newly emerged adult obtained a lower threshold temperature of 9.9°C. This estimate is very similar to the lower threshold temperature obtained for the pupal stage in this study. Howell & Neven (2000) reported lower threshold temperatures of 6.9, 9.3 and 10.3°C for the larval stage depending on how many points that deviated from linearity were used to calculate the lower threshold. These authors suggest that codling moth development time can be more accurately determined in the field using field-simulated temperature data than constant temperatures.

Calculation of the degree-day required to complete development of the egg, larval and pupal stages was based on the lower threshold temperatures derived from the laboratory studies. The overall degree-day estimates required to complete development of the egg, larval and pupal stages were 80.5, 345 and 279°D representing 11.43, 48.97 and 39.60% of the mean duration of a total developmental period of 704.5°D. The degree-days requirements for the egg, larval and pupal stages and mean duration for total development of codling moth was higher in this study than that given by other researchers (Table 13). The degree-day requirements presented by Glenn (1922), Riedl & Croft (1978), Rock & Shaffer (1983) and Pitcairn *et al.* (1991) are all based on a threshold temperature of 10°C. Using the most commonly reported lower threshold temperature for development in the literature, 10°C (Pitcairn *et al.* 1991), the average number of degree-days required to complete development of the egg, larval and pupal stages in this study would be 91.2, 281.90 and 276.00°D respectively. The mean duration of total development would be 649.10°D which is comparable to that of Pitcairn *et al.* (1991) and Glenn (1922). Using a lower threshold temperature of 10°C and the 5 fastest development times for each replication of each life stage, the development times for the egg, larvae and pupae were 82.20, 215.38 and 239.58°D respectively.

Based on these figures the minimum period for a generation was 505°D which is very similar to the minimum generation time of 525.5°D given by Riedl & Croft (1978). At a base of 10°C the larval and pupal development times are similar to those of Rock & Shaffer (1983).

Degree-day requirements for eggs, larvae and pupae under variable temperature conditions were based on the lower threshold temperatures derived for each stage from the laboratory studies of development rate at constant temperature conditions. The egg, larval and pupal stages required a mean of 78.55, 367.19 and 283.60°D respectively to complete development with a mean duration of 729.6°D for the total development period. The average number of degree-days to complete a life cycle (from egg to adult) under variable temperature conditions was similar to that obtained at constant temperatures (704.5°D). The greatest variation occurred during the incubation period at average ambient temperatures below 17.19°C. This is attributed to night and early morning temperatures on numerous occasions falling below 8.5°C, which is below the developmental threshold of the egg, and a decrease in the linear relationship between temperature and time at temperatures below 17°C. However, the similarity in degree-day requirements under constant and variable temperature conditions suggests that the estimates of the lower threshold temperatures can be incorporated into a phenology model.

Current control recommendations for codling moth stipulate commencement of the spray programme at full-bloom of the earliest cultivars. In the case of pear cultivars grown in the cooler production areas of South Africa, full-bloom of the earliest flowering cultivar can occur between the beginning and end of September depending on temperature conditions. Under cool conditions egg hatch may occur several weeks after full-bloom. Degree-day prediction for first egg hatch using pheromone traps to accurately pin-point the commencement of the first moth flight can improve the timing of the first cover spray and reduce spray costs. Information on degree-day requirements will also lead to a better understanding of the seasonal occurrence of codling moth.

The base temperature (lower threshold temperature for development) for codling moth in the literature has been reported to range from 8°C to 11.1°C (Howell & Neven 2000). In this study the lower threshold for development varied from 7.89°C for the pupal stage to 11.06°C for the egg stage. Despite this range the most commonly reported lower threshold temperature for codling moth in the literature is 10°C (Pitcairn *et al.* 1991). Although a lower threshold temperature was obtained for each of the embryonic and immature stages of codling moth in this study, it would be more practical to select the most universally applied lower threshold temperature for codling moth, 10°C, incorporate it in a phenology

model and evaluate the models accuracy to predict first egg hatch and commencement of the second generation. The mean of the lower threshold temperatures obtained in this study is 9.6, with a lower mean of 7.6 and an upper mean of 11.6 at the 95 % confidence interval. This is sufficiently close enough to 10°C to justify using this lower threshold temperature in a phenology model in South Africa. The results of such studies are reported on in Chapter 4.

2.4.2 Longevity

Constant and fluctuating temperatures were used independently in studies to determine the longevity of adults of the spring and summer generations. This provided a more complete understanding of this aspect of the biology of codling moth than studies at either constant or fluctuating temperature could have given on their own. From the observations, as well as those of other authors, it is evident that temperature is an important parameter in the longevity of codling moth adults, longevity decreasing with increasing temperature. Over a temperature range of 6°C there was a decrease in mean longevity of 18.3 days at constant temperatures. The longevity of adults exposed to fluctuating temperatures also showed a similar trend to that obtained under constant temperatures, i.e.decreasing longevity with increasing temperature.

The mean longevity of spring generation adults exposed to constant temperatures of 19°C and 21°C was similar to the longevity of spring adults exposed to fluctuating spring temperatures. This similarity was probably due to the temperatures during the spring observation period being comparable to the two lower temperatures spring adults were exposed to at constant temperatures. There were no differences in longevity between spring and summer generation moths at constant temperatures. However, at fluctuating temperatures the spring generation adults lived significantly longer than summer adults. There was also no significant difference between the sexes of the summer adults, both living for between 11 and 12 days. Furthermore, the overall mean adult longevity of summer adults (11.7 days) exposed to fluctuating summer temperatures was half the overall mean adult longevity (22.5 days) at constant temperatures. This difference can be attributed to the high temperatures, in excess of 30°C, adults were exposed to during the summer observation period. It would appear that the high temperatures during summer could have a considerable negative impact on the longevity of summer moths. These findings differ to some extent from those of other researchers. Hagley (1972) also observed a decrease in longevity with an increase in temperature at constant temperatures, using moths reared on immature green apples. However, there was little variation in longevity between adults of different sexes. Geier (1963) reported a mean female longevity of 12 days under fluctuating spring and summer temperatures, there

being no difference in longevity between spring and summer adults despite the use of field collected moths. Selkregg & Siegler (1928) also found little seasonal variation in longevity. The average longevity of spring and summer adults was between 8 and 9 days and 7 and 8 days respectively. Hathway *et al.* (1971) reported a much lower average adult longevity that varied between 5.4 and 7.0 days for females and between 6.1 and 9.5 days for males reared on different artificial diets or immature green apples at 26.7°C. Moffitt & Albano (1972) obtained similar results for adults from larvae reared on immature green apples. Howell (1981) found that at a high constant temperature of 26.7°C laboratory reared moths lived significantly longer when provided with water (12.9 days) compared to no water (4.7 days). In the present study the moths were provided with water twice daily and the mean longevity of summer moths (11.7 days) was similar to the findings of Howell (1981). During the dry hot summer months the availability of free water in the form of dew or rain will be scarce and may have a adverse impact on longevity.

Although the longest recorded longevity of a female moth at constant temperatures was 49 days, it is unlikely that this would ever be achieved under natural conditions. The results under fluctuating temperatures, suggest that adults in the earlier and cooler part of the season will live the longest. Based on the mean longevity and standard deviation obtained under fluctuating temperatures the female moth will probably live from 14 to 24 days in spring and 7 to 17 days in summer.

2.4.3 Oviposition period

There was no difference in the duration of the oviposition period of spring and summer generation moths at constant temperatures, the oviposition period decreasing by almost 50 % with only a 6°C increase in temperature. This is contrary to the findings at fluctuating temperatures, where the mean duration of the oviposition period of the spring adults was significantly longer than that of the summer moths. The results obtained from constant temperature and humidity conditions suggest that there is no difference in the quality or "fitness" of spring and summer females. This is surprising as the spring generation females arose from mature larvae overwintering in the orchard from the end of January to September/October, a period of 8 to 9 months, while the summer generation moths arose from mature larvae that immediately pupated after leaving the fruit from December to February. At fluctuating temperatures the higher temperatures during the summer observation period compared to those during the spring observation period, would appear to have reduced the duration of the oviposition period of the summer moths.

The findings are similar to those of previous researchers. Hagley (1972) reported a correlation between longevity and duration of the oviposition period which varied from 4 to 15 days at a constant temperature of 24°C. Isely (1938) showed that at fluctuating summer temperatures, over a mean temperature range of 21°C to 33°C, the oviposition period was approximately 7 days, although individual moths oviposited for up to 20 days. However, Selkregg & Siegler (1928) reported an oviposition period of between 7 and 8 days for both the spring and summer generations, with a maximum period of 17 days.

2.4.4 Time to peak, 50% and 80% oviposition

In the present study there were no significant differences in the mean number of days between mating to peak oviposition, and to 50% and 80% of total eggs laid for the spring and summer moths at constant temperatures. However, at fluctuating temperatures there was a significant difference between seasonal generations, with peak, 50 % and 80% oviposition of summer moths occurring in half the time that it occurred in spring. The difference between constant and fluctuating temperatures is probably due to the moths being exposed to a greater daily range and higher temperatures under fluctuating temperatures. During the spring period there were many evenings when the temperature was below 15°C or above 15°C for a very short period, resulting in very low egg production. The mean duration of the nightly oviposition period in spring was 2 hrs (SD = ± 1.21) with a range of 1 - 6 hrs (n = 196), while in summer the oviposition period was 2.7 hrs (SD = ±1.65) with a range of 1-9 hrs (n = 167). Previous researchers have also reported very short periods between peak, 50% and 80% oviposition, particularly at high temperatures. Howell (1981) found that oviposition was heaviest on the second and third day of adult life and 90% completed by the fifth day at 26.7°C. Riedl & Loher (1980) recorded peak oviposition on the first day, 50% eggs produced by the third day and 90% completed by the ninth day. At fluctuating temperatures Isely (1938) reported summer oviposition being highest on the first day and 90% completed by the seventh day. In spring 16% of eggs were deposited on the first day and 90% completed by the 12 day.

2.4.5 Eggs per female

The mean fecundity of the spring moths at constant and fluctuating temperatures (90.9 and 92.6 eggs/female respectively) was very similar, suggesting similar range of oviposition conditions. Although summer generation moths (163.5) produced significantly more eggs per female than the spring moths (90.9) at constant temperatures there were no generation differences in fecundity at fluctuating

temperatures. This is probably a reflection of the adverse temperature conditions in summer. Fecundity studies using branches, enclosed in nylon netting, in the orchard (Chapter 3) produced higher mean fecundity levels than that obtained at fluctuating temperatures in the open insectary. The fecundity of codling moth cited in the literature is highly variable as studies have involved feral females and females from laboratory colonies reared on artificial medium or immature apples. The present study was concerned with the oviposition of feral females and the findings suggest that the fecundity of codling moth in South African orchards is one of the highest in the world. The fecundity of feral females from various regions of the world is given in Table 14. Where the fecundity of seasonal generations have been researched separately the summer generations have been shown to have the highest fecundity. However, in many of the studies there was very little difference in fecundity between the seasonal generations (Allman,1928; Hall, 1929; Miller, 1943; Tadic, 1957; Chang *et al.* 1960 and Geier 1963). However, Hall (1929) and Deseö (1973) reported that females of the spring generation produced up to 80% fewer eggs than the summer female moths. Where fecundity has been found to vary between and within seasons this variation has been attributed to variations in climatic factors, such as either unfavourable temperatures (Isely, 1938) or snowfall (Trottier & Hagley, 1979) rather than food quality which has also been cited as a reason for variation in fecundity (Wearing & Ferguson, 1971). Deseö (1971) found a positive correlation between adult weight and fecundity, while Hathaway (1973) found no relationship between pupal weight and fecundity. Geier (1963) reported a significant difference between the mean body weights of the spring, early summer and late summer moths, but the differences were considered too slight to affect fecundity. In the present study significant differences could be found between the female pupal weights of the spring period and those of the early summer and late summer periods. Little oviposition took place at or below 16°C and above 27°C, suggesting that this is the optimum temperature range for oviposition.

2.4.6 Eggs per day

Although summer moths laid more eggs than spring moths at the lower constant temperatures there was no significant difference in the mean daily egg production between the spring and summer moths. At fluctuating temperatures the mean daily egg production per female in summer (16.5) was almost double that in spring (7.7) but the difference was also not significant. This could be due to the wide variation in the number of eggs laid per day. Isely (1938) found that mean daily egg production per female of summer moths was highest at 27°C (19.2) and lowest at 33°C (7.0) and 22°C (6.7). He also found that periods of high temperatures (heat waves) during the final stages of pupal development had an adverse effect on

fecundity. Howell (1981) reported from Newcomer & Whitecomb (1924) that daily oviposition was 5-8 eggs. The high number of eggs that was produced by a female in an evening (111) and the number of evenings when more than 25 eggs per female were oviposited suggest that under optimum conditions a considerable number of eggs can be laid in an evening, particularly if adverse conditions have delayed oviposition for a number of days. Isely (1938) and Riedl & Loher (1980) also observed days of high oviposition/egg production followed by days of low egg production. In the present study periods of high egg production were often followed by periods of low or no egg production at constant temperatures. This phenomenon was more evident at 15°C than at 21°C, particularly for the summer generation moths. The periods of no egg production extended from 1 to 10 days at 15°C and 1 to 3 days at 21°C. The number of days when no eggs were laid at 15°C and 21°C was 135 (out of 324 oviposition evenings) and 15 (out of 131) respectively. The trend for the spring and summer moths was similar. For the spring and summer moths periods of no egg production also extended from 1 to 10 days and 1 to 3 days respectively. The extended periods of no oviposition often occurred toward the end of the oviposition period. These observations suggest that daily egg production will be more extended and erratic during the spring than during the summer period.

2.4.7 Mating

Most matings took place between 18h00 and 22h00, no matings taking place below 15°C. On one of the occasions that mating did take place between 15°C and 16°C the moths were still found in copula the following morning. The highest temperature at which moths were observed mating was 26°C. Van Leeuwen (1929) observed that most matings occurred between 19h00 and 21h00. Based on the assumption that pheromone trap catches and period of mating are synchronous (Howell 1991), Wong *et al.* (1971) showed that peak sexual activity was during the hour immediately after sunset. Borden (1931) and Cutright (1964) also reported peak mating shortly after sunset. However, contrary to these findings Castrovillo & Carde (1979) found that most female calling was confined to darkness, although periodically females called prior to and shortly after the scotophase. Maximum calling was one hour after sunset and lasted for 1.5 hours. Thereafter it declined and terminated at sunrise. In the present study most of the matings observed in October occurred prior to and just after sunset, suggesting that under the cool spring conditions most matings occurred while it was still light. During November 56% of the matings took place during darkness and at temperatures higher than during October. This is in accord with the findings of Batiste *et al.* (1973), i.e. that the flight activity and consequently mating is advanced under cool conditions.

2.4.8 Head capsule widths

Dyar (1890) observed that the width of the head capsule of a larva in its successive stages increased in a regular geometrical progression. At a constant temperature of 25°C the ratio of increase in head capsule width between successive instars was almost constant varying from 1.47 to 1.53 indicating that no intermediate instars were present. Contrary to the results of Williams & McDonald (1982) there was minimal overlapping of the ranges of successive instars. The duration of each larval instar and the complete larval stage corresponded to the periods given by Williams & McDonald (1982) for 25°C. Female larvae developed marginally faster than males. This was contrary to the results obtained for the larval development rates at constant temperatures and those of Williams & McDonald (1982) and Geier & Briese (1978). However, the differences are probably too small to be meaningful. The degree-days required to complete the larval period was comparable to that found by other researchers when based on a lower threshold temperature of 10°C (Riedl & Croft 1978; Williams & McDonald 1982; Pitcairn *et al.* 1991).

Despite the difference in time of year and fruit maturity, the ratio of increase in head capsule width at fluctuating temperatures during December and February was very similar, varying from 1.42 to 1.55. The similarity between the mean head capsule widths and ranges for each instar reared on fruit of different stages of development suggests that fruit development has little influence on mean head capsule width or range of each instar.

The aim of the study was not to establish a probability level for classifying an individual larva into a particular instar but rather to estimate a range of head capsule widths for each instar based on the estimated mean head capsule width for each instar. Because of the small size of the head capsule, and measurements being rounded-off to only 2 decimal positions, very little variance occurs in the data. This results in small standard deviations and even smaller standard errors. Consequently even a difference of 0.01 between two means becomes statistically significant. Concentrating on statistical differences between means masks the fact that the two sets of data are in fact very similar.

The head capsule widths of instars reared at a constant temperature on mature apples were marginally smaller than those reared at fluctuating temperatures.

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Table 1. Mean development times and degree-days (°D) of *Cydia pomonella* eggs, larvae and pupae at five constant temperatures.

Life stage	Temp (°C)	n	Developmental time (days ± SD)	Range	°D ± SD	°D ± SD (Base 10°C)
Egg	15	570	19.39 ± 0.622	18.6-20.8	76.43 ± 2.45	97.00 ± 3.11
	17	505	13.76 ± 0.581	12.0-15.8	81.59 ± 3.45	96.15 ± 4.07
	20	574	9.19 ± 0.433	8.0-10.7	82.15 ± 3.87	91.90 ± 4.33
	25	515	5.75 ± 0.220	5.0 - 6.9	80.18 ± 3.06	86.27 ± 3.29
	30	474	4.23 ± 0.312	3.8- 4.9	80.19 ± 5.91	84.68 ± 6.24
					80.1	91.2
Larva	15	179	48.94 ± 6.711	38.0-70.0	347.50 ± 47.60	244.72 ± 33.55
	17	196	39.68 ± 6.476	29.0-61.0	361.12 ± 59.70	277. 79 ± 45.99
	20	235	26.19 ± 3.423	18.0-38.0	316.92 ± 41.40	261.91 ± 34.23
	25	224	21.07 ± 3.653	15.0-34.0	360.25 ± 62.40	316.00 ± 54.80
	30	266	15.46 ± 2.316	12.0-26.0	341.55 ± 54.40	309.10 ± 49.56
					345.5	281.9
Pupa	15	215	56.25 ± 10.065	42.0-109.0	288.41 ± 51.60	281.28 ± 50.79
	17	164	37.90 ± 3.510	31.0-53.0	270.20 ± 25.00	265.27 ± 24.58
	20	156	27.48 ± 3.474	22.0-43.0	278.38 ± 35.00	274.81 ± 34.63
	25	166	18.88 ± 4.082	14.0-34.0	285.64 ± 61.70	282.18 ± 60.01
	30	173	13.78 ± 2.233	11.0-27.0	277.40 ± 44.90	275.61 ± 44.66
					280.0	275.8
Pre-oviposition	15	13	7.54 ± 2.847	3.0-14.0	27.14 ± 10.20	37.69 ± 13.01
	17	13	4.31 ± 1.109	3.0-6.0	24.12 ± 6.20	30.15 ± 7.77
	19	13	3.23 ± 0.927	2.0-5.0	24.55 ± 7.00	29.07 ± 8.3
	21	13	2.54 ± 0.436	2.0-4.0	24.37 ± 6.30	27.92 ± 7.26
					25.0	31.2

Table 2. Mean observed development times, estimated development times, and mean observed degree-days (°D) required for development of *Cydia pomonella* eggs, larvae and pupae at fluctuating temperatures.

Life stage	Mean temperature (°C)	n	Observed Development time (days ± SD)	Estimated development time (days)	Observed °D (± SD)
Egg	14.87	115	15.51 (± 0.161)	21.11	72.04 (± 7.964)
	15.47	117	13.90 (± 0.390)	18.24	68.54 (± 2.645)
	16.10	138	12.49 (± 0.588)	15.96	72.37 (± 8.660)
	17.09	138	11.63 (± 0.117)	13.34	66.72 (± 1.459)
	19.26	122	9.23 (± 0.382)	9.81	82.77 (± 4.090)
	20.15	169	8.95 (± 0.171)	8.85	84.95 (± 4.841)
	20.66	159	8.57 (± 0.207)	8.38	93.04 (± 4.976)
	22.27	188	6.97 (± 0.216)	7.18	87.50 (± 6.011)
	23.08	156	6.95 (± 0.272)	6.70	78.80 (± 5.628)
	27.46	123	6.67 (± 0.054)	6.49	78.81 (± 0.0001)
Larva	19.67	62	30.06 (± 4.602)	29.28	357.97 (± 51.418)
	20.17	88	29.72 (± 4.741)	28.09	390.25 (± 58.315)
	21.03	74	24.20 (± 3.990)	26.25	336.41 (± 57.367)
	22.01	73	25.52 (± 3.069)	24.43	373.13 (± 48.424)
	22.15	133	24.68 (± 5.140)	24.19	381.66 (± 52.450)
	22.99	95	23.26 (± 3.955)	22.84	356.53 (± 58.428)
	23.38	90	23.67 (± 3.573)	22.27	360.90 (± 58.428)
	23.40	119	23.33 (± 3.811)	22.24	380.65 (± 59.843)
Pupa	22.30	191	23.88 (± 2.743)	22.47	279.62 (± 39.480)
	22.26	143	24.07 (± 2.838)	22.54	291.98 (± 47.648)
	23.30	97	20.33 (± 2.947)	22.79	289.33 (± 37.093)
	22.97	124	21.04 (± 3.933)	21.27	290.40 (± 31.698)
	22.67	164	21.14 (± 2.036)	21.83	274.77 (± 27.459)
	23.15	127	20.19 (± 1.607)	21.02	276.72 (± 21.904)
	23.70	163	19.20 (± 1.825)	20.18	282.37 (± 26.450)

Table 3. Mean development time (days) of *Cydia pomonella* male and female larvae and pupae at five constant temperatures.

Temperature (°C)	Development time (days ± SD)			
	Male			
	n	Larva	n	Pupa
15	81	47.80 (± 6.435)	111	56.25 (± 9.915)
17	100	38.87 (± 6.326)	88	37.91 (± 3.358)
20	123	25.85 (± 3.234)	65	27.94 (± 3.588)
25	121	20.66 (± 3.572)	81	19.69 (± 4.443)
30	135	15.15 (± 2.796)	86	13.99 (± 2.364)
	Female			
	n	Larva	n	Pupa
15	63	49.05 (± 6.797)	102	56.07 (± 10.305)
17	81	40.05 (± 6.569)	76	37.88 (± 3.702)
20	110	26.58 (± 3.626)	91	27.13 (± 3.702)
25	102	21.53 (± 3.799)	83	17.98 (± 3.407)
30	126	15.84 (± 2.207)	87	13.59 (± 2.084)

Table 4. Mean development times (days) of *Cydia pomonella* male and female larvae and pupae at fluctuating temperatures.

Life stage	Mean Temp. (°C)	Mean Development time (days ± SD)			
		n	Male	n	Female
Larva	21.03	21	22.57 ± 2.821	26	24.46 ± 4.420
	21.67	25	21.12 ± 4.693	31	22.16 ± 4.576
	22.01	28	26.18 ± 3.031	37	26.62 ± 2.994
	22.99	33	22.33 ± 3.663	40	23.34 ± 3.759
	23.38	15	23.53 ± 4.749	27	23.44 ± 3.388
Pupa	22.26	92	24.48 ± 3.307	51	23.33 ± 1.451
	22.67	112	21.40 ± 2.165	51	20.57 ± 1.510
	22.97	82	21.55 ± 2.846	42	20.67 ± 1.748
	23.15	72	20.15 ± 1.607	55	20.24 ± 1.621
	23.30	60	20.67 ± 2.995	39	19.95 ± 2.724
	23.70	90	19.30 ± 1.748	71	19.07 ± 1.923

Table 5. Mean longevity (days) and oviposition of *Cydia pomonella* of the spring (September to November) and summer (January to February) periods at fluctuating temperatures.

Period	Longevity (days ± SD) (range) [n]		Mean duration of oviposition period (days ± SD) (range) [n]	Mean daily number of eggs/female (days ± SD) (range) [n]	Mean number of eggs/female (eggs ± SD) (range) [n]	Mean number of days after mating to:		
	Male	Female				Peak oviposition (±SD) (range) [n]	50% of eggs laid (±SD) (range) [n]	80% of eggs laid (±SD) (range) [n]
Spring	17.1 ± 6.82 (5 - 38) [40]	21.5 ± 6.91 (11 - 39) [40]	11.7 ± 6.26 (1 - 25) [40]	7.7 ± 11.24 (0 - 72) [470]	92.6 ± 62.21 (7 - 222) [40]	5.1 ± 3.7 (1 - 17) [40]	7.0 ± 4.2 (3 - 22) [40]	10.7 ± 5.1 (3 - 25) [40]
Summer	11.4 ± 6.47 (3 - 38) [34]	11.9 ± 4.67 (4 - 23) [40]	7.4 ± 4.92 (1 - 21) [40]	16.5 ± 18.80 (0 - 111) [293]	121.2 ± 77.99 (1 - 303) [40]	2.2 ± 1.21 (1 - 5) [40]	3.3 ± 2.23 (1 - 12) [40]	5.3 ± 3.29 (1 - 14) [40]

Spring: The duration of the nightly oviposition period (hrs) was 2.0 (SD = ± 1.21) with a range of 1 to 6 hrs (n = 196).

Summer: The duration of the nightly oviposition period (hrs) was 2.7 (SD = ± 1.65) with a range of 1 to 9 hrs (n = 167).

Table 6. Linear regression functions of time from mating to 50 % and 80 % oviposition over temperatures of 15, 17, 19 and 21°C.

Mating to:	Seasons	Regression function (SE)
50 % oviposition	Spring	$1/y = -0.2153 + 0.0193x \quad r^2 = 0.82$ (0.1168) (0.0064)
	Summer	$1/y = -0.2170 + 0.0197x \quad r^2 = 0.99$ (0.0194) (0.0011)
	Pooled	$1/y = -0.2161 + 0.0195x \quad r^2 = 0.90$ (0.0489) (0.0027)
80 % oviposition	Spring	$1/y = -0.1175 + 0.0118x \quad r^2 = 0.80$ (0.0755) (0.0042)
	Summer	$1/y = -0.1569 + 0.0136x \quad r^2 = 0.98$ (0.0230) (0.0013)
	Pooled	$1/y = -0.1372 + 0.0127x \quad r^2 = 0.88$ (0.0348) (0.0019)

Table 7. Head capsule widths of instars 1 to 5 of 31 *Cydia pomonella* larvae reared at 25°C on mature Golden Delicious apples.

Instar no.	Head capsule width (mm)			Ratio of increase
	Mean	SD	Range	
1	0.349	0.014	0.32-0.37	-
2	0.498	0.024	0.45-0.54	1.43
3	0.762	0.043	0.66-0.86	1.53
4	1.103	0.075	0.94-1.23	1.45
5	1.571	0.076	1.44-1.72	1.42

Table 8. Mean duration (days), mean degree-days (°D) and range of instars 1 to 5 of 31 *Cydia pomonella* larvae at 25°C on mature Golden Delicious apples.

	Duration					Mean duration from egg hatch to cocoon formation	
	Instar no.						
	1	2	3	4	5	Male	Female
Days	4.0	4.1	4.3	4.6	5.1	21.3	20.8
°D *	68.0	70.4	74.1	78.4	87.2	375.1	366.6
°D **	59.7	61.7	65.0	68.8	76.5	321.6	329.0
Range	3-8	4-6	2-7	3-7	4-7	19-27	19-27

* °D based on a lower threshold temperature of 7.9°C.
** °D based on a lower threshold termperature of 10°C.

Table 9. Head capsule widths of instars 1 to 5 of *Cydia pomonella* larvae reared on apples in caged branches of Golden Delicious trees in an unsprayed apple orchard between the 29/11/88 and 6/1/89.

Instar no.	Head capsule width (mm) (99% Conf. Interval)				Ratio of increase
	n	Mean	SD	Range	
1	57	0.35	0.012	0.31 - 0.39	-
2	99	0.50	0.026	0.42 - 0.58	1.43
3	105	0.73	0.055	0.57 - 0.90	1.46
4	65	1.13	0.091	0.86 - 1.40	1.55
5	141	1.65	0.094	1.37 - 1.93	1.46

Table 10. Head capsule widths of instars 1 to 5 of *Cydia pomonella* larvae reared on apples in caged branches of Golden Delicious trees in an unsprayed apple orchard between the 2/2/89 and 6/3/89.

Instar no.	Head capsule width (mm)				Ratio of increase
	n	Mean	SD	Range	
1	51	0.34	0.013	0.30 - 0.38	-
2	142	0.50	0.028	0.42 - 0.58	1.47
3	105	0.77	0.048	0.63 - 0.91	1.54
4	149	1.15	0.070	0.94 - 1.36	1.49
5	194	1.63	0.086	1.37 - 1.89	1.42

Table 11. Composition of instars 1 to 5 of *Cydia pomonella* larvae on Golden Delicious apples sampled at intervals from caged branches between the 5/12/88 and 06/1/89 and degree-days (°D) on each sample date based on a lower threshold temperature of 7.9°C. Apples seeded with neonate larvae on 29/11/88.

Date	°D	Instars no.					Total
		1	2	3	4	5	
05/12/88	68.0	45	3				45
08/12/88	107.4	15	35				50
12/12/88	142.3	1	41	8			50
15/12/88	165.5	0	19	29	2		50
19/12/88	212.9	0	0	39	10		49
22/12/88	252.1	0	0	26	19	4	49
27/12/88	311.0	0	0	1	19	31	51
30/12/88	353.9	0	0	1	11	41	53
02/01/88	401.5	0	0	0	8	42	50
06/01/88	453.1	0	0	0	0	23	23

Table 12. Composition of instars 1 to 5 of *Cydia pomonella* larvae on Golden Delicious apples sampled at intervals from caged branches between 7/2/89 and 6/3/89 and degree-days (°D) on each sample date based on a lower threshold temperature of 7.9°C. Apples seeded with neonate larvae on 02/02/89.

Date	°D	Larval instars					Total
		1	2	3	4	5	
06/02/89	64.30	49	0	0	0	0	49
08/02/89	96.00	2	49	0	0	0	51
10/02/89	125.2	0	50	0	0	0	50
13/02/89	161.2	0	31	19	0	0	50
15/02/89	182.1	0	12	37	0	0	49
17/02/89	207.6	0	0	44	0	0	44
20/02/89	248.9	0	0	4	42	3	49
22/02/89	270.5	0	0	2	43	5	50
24/02/89	291.4	0	0	0	29	20	49
27/02/89	324.4	0	0	1	16	31	48
01/03/89	345.6	0	0	0	10	40	50
03/03/89	362.0	0	0	0	4	46	50
06/03/89	394.7	0	0	0	0	50	50

Table 13. Summary of mean °D requirements for the egg, larva and pupa of *Cydia pomonella* from its present study and for comparison purposes those of Pitcairn (1991), Glenn (1922) and Riedl & Croft (1978).

Stages	Present Study	Pitcairn *et al.*(1991)	Glenn (1922)	Riedl & Croft (1978)
Egg	80.5	93.9	90.6	87.8
Larva	345.0	280.6	373.9	295.5
Pupa	279.0	256.0	147.2	142.2
Total	704.5	631.5	611.7	525.5

Table 14. Recorded * fecundity of feral codling moth, *Cydia pomonella* (L.)

Reference	Region	Generation	Mean fecundity
Blomefield (present study)	Western Cape Province, SA	spring	92.6
		Summer	121.2
Le Baron (1873)	Illinois, USA	unspecified	50
Simpson (1903)	USA	unspecified	30 - 40
Glenn (1922)	Illinois, USA	unspecified	31 - 42
Isley & Ackerman (1923)	Arkansas, USA	spring	8
		summer	52
Reh (1925)	Central Europe	unspecified	20 - 80
Allman (1928)	Bathurst, NSW	spring	22
		summer	26
Hall (1929)	Ontario, Canada	spring	64
		summer	83
alachowsky & Mesnil (1935)	Western Europe	unspecified	20
Wiesmann (1935)	Switzerland	unspecified	50
Miller (1943)	Victoria, Australia	spring	5
		summer	7
		late summer	15
Tadic (1957)	Yugoslavia	spring	39
		summer	37
Chang *et al.* (1958)	China	unspecified	91
Chang *et al.* (1960)	Sinkiang, China	spring	33
		summer	43
Coutin (1960)	France	unspecified	50
Proverbs & Newton (1962)	Canada	summer	33
Geier (1963)	Australia	spring	44
		summer	44
Arias & Nieto (1972)	Spain	spring	33
		summer	63
Wearing & Ferguson (1971)	New Zealand		
1967 - 68		unspecified	44.9
1968 - 69		unspecified	89.5
1969 - 70		unspecified	47.1
Deseö (1973)	Hungary	spring	16.8
		summer (1st)	88.3
		summer (2nd)	36.6
Cisneros & Barnes (1974)	California USA	unspecified	
		apple	89
		walnut	58
Esteban-Duran (1975)	Spain	spring	47
		summer	78
Ferro *et al.* (1975)	Washington State USA		
1973		summer	42
1974		summer	37
Trottier & Hagley (1979)	Ontario, Canada	spring	9.7 - 32.9

* From Geier (1963), Ferro *et al.* (1975) and Howel, (1991).

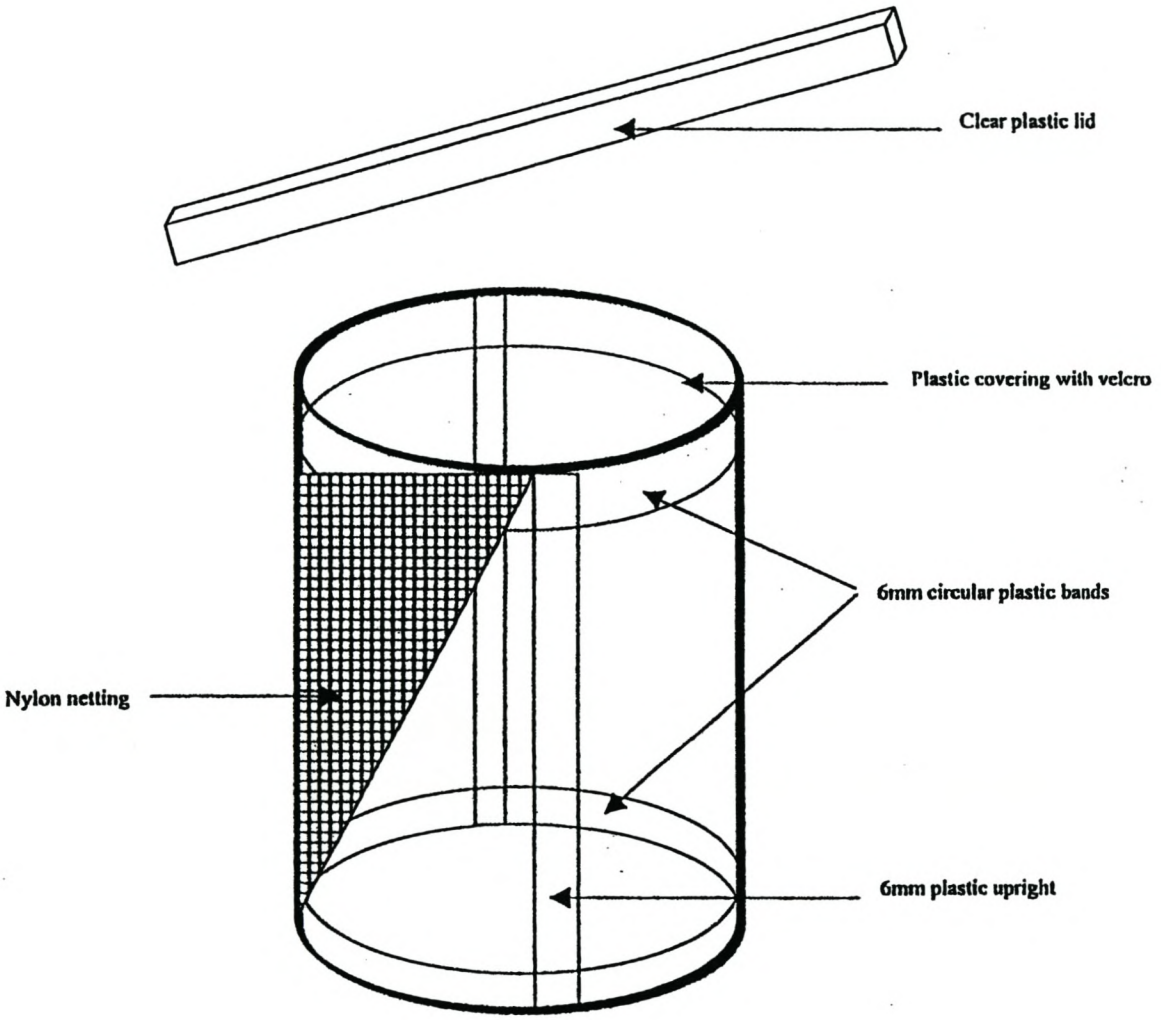

Fig. 1. Cylindrical nylon cages were used for oviposition trials at constant and fluctuating temperatures.

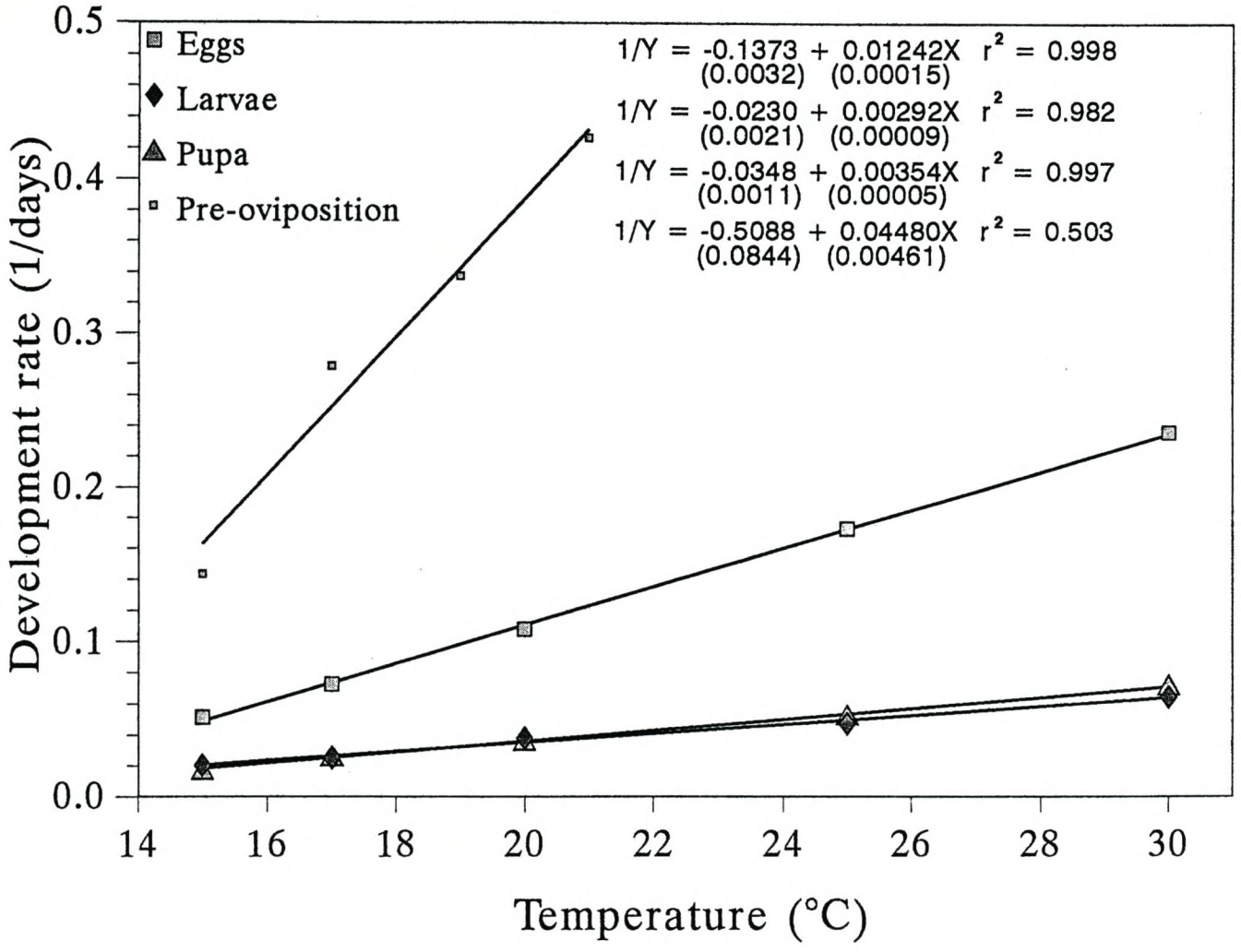

Fig. 2. Rate of *Cydia pomonella* egg, larva and pupa development at five constant temperatures. The symbols represent the mean development rate at each temperature.

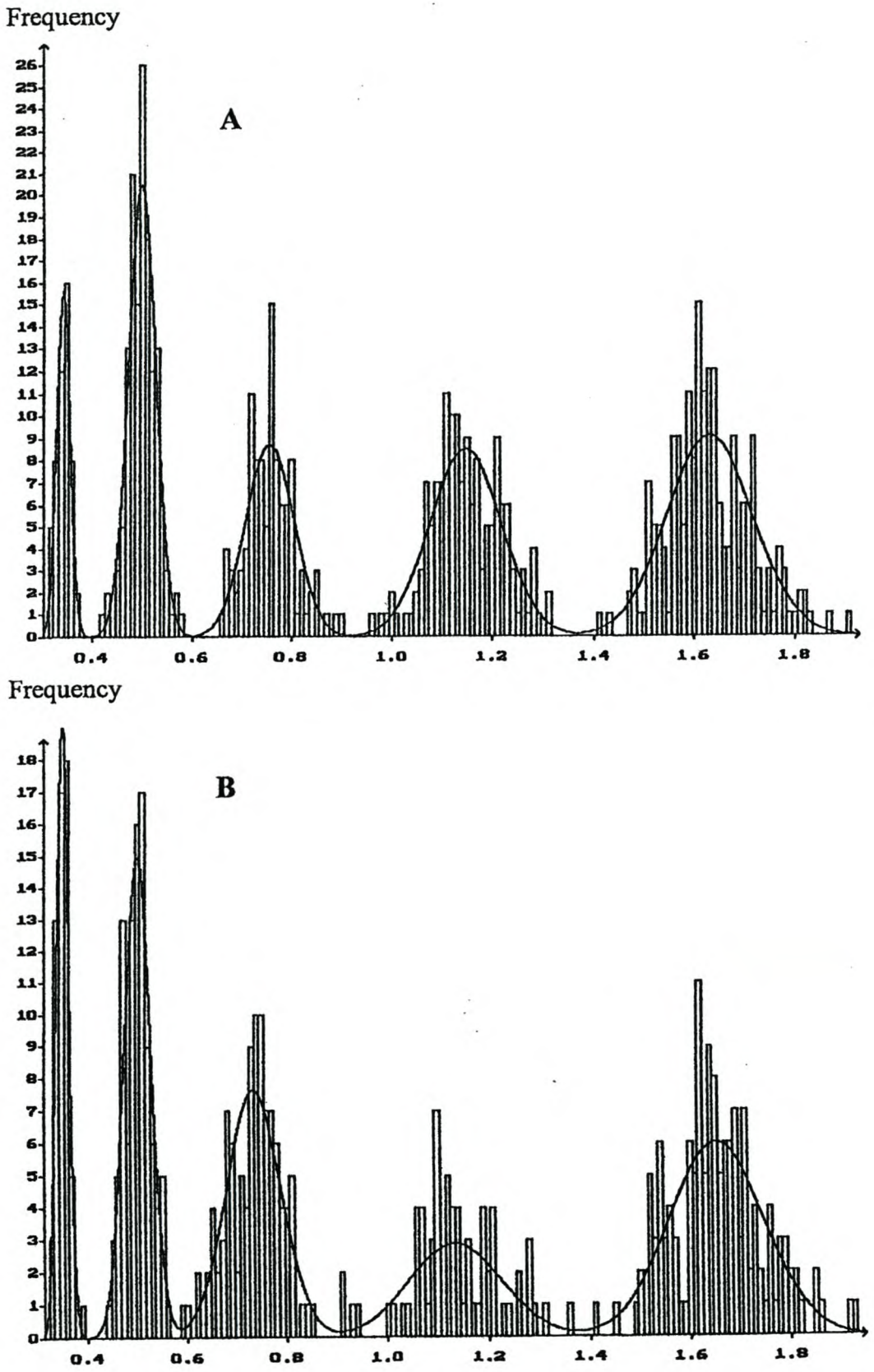

Fig. 3. Frequency distribution of observed head capsule widths of *Cydia pomonella* larvae reared on caged Golden Delicious apples between (A) 29/11/88 and 6/1/89 and (B) 2/2/89 and 6/3/89 in an unsprayed apple orchard. Frequency distribution curves are fitted to each instar group.

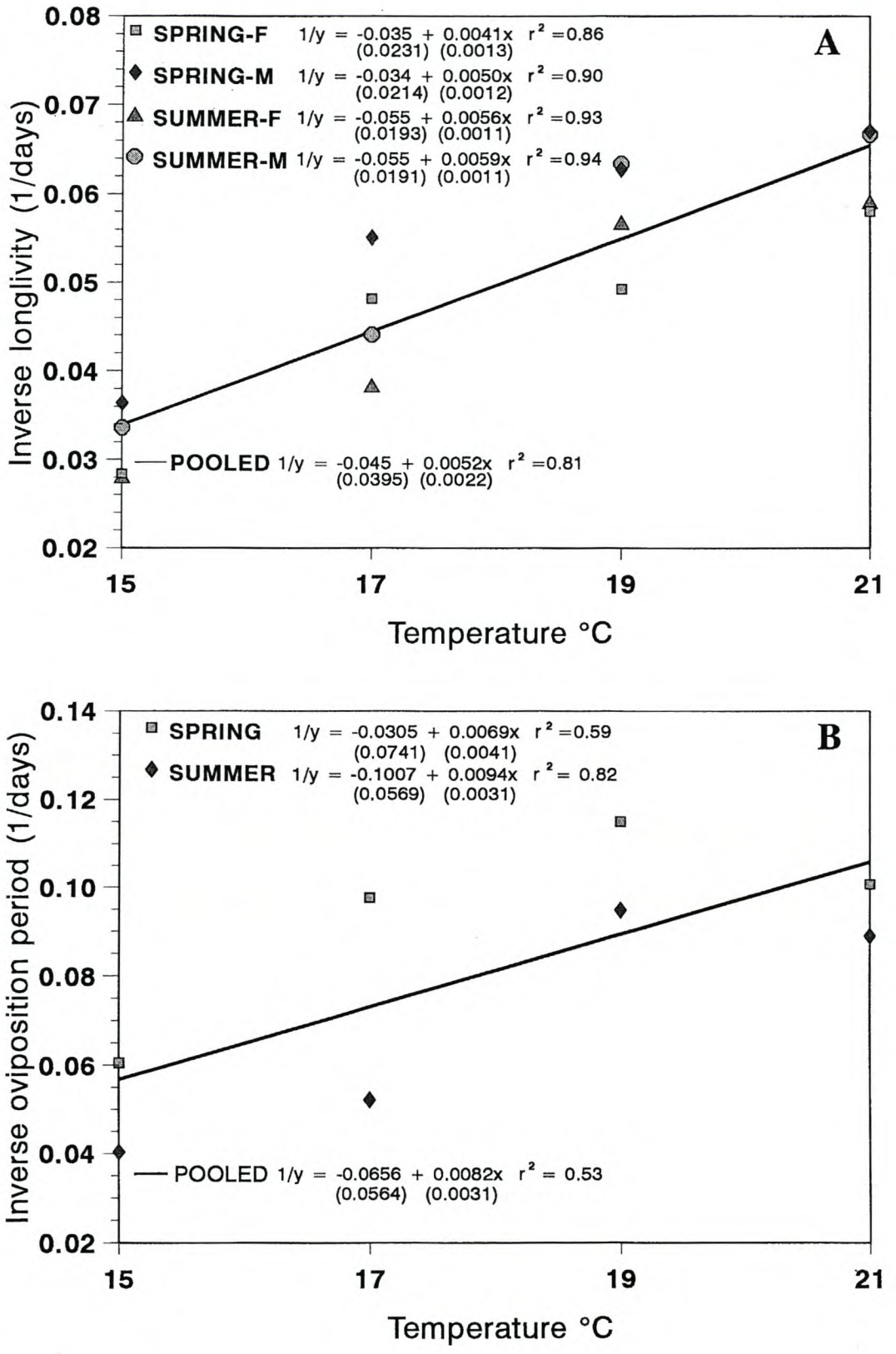

Fig. 4. Relationship between temperature and the inverse of (A) longevity of males (M) and females (F) and (B) oviposition period of *Cydia pomonella* of the spring and summer generations (Standard error given in parenthesis).

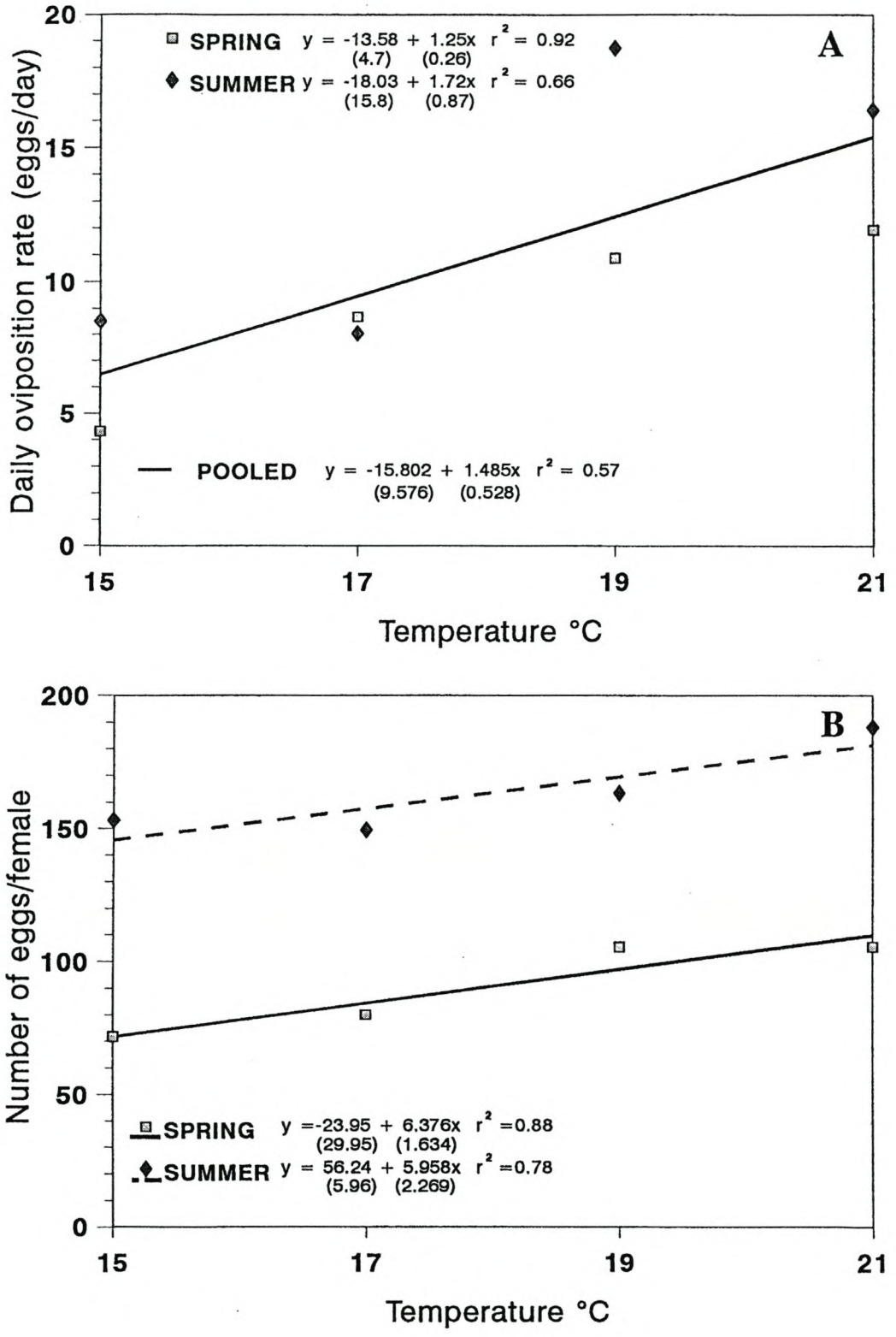

Fig. 5. Relationship between temperature and (A) daily oviposition and (B) number of eggs per female of *Cydia pomonella* of the spring and summer generations (Standard error given in parenthesis).

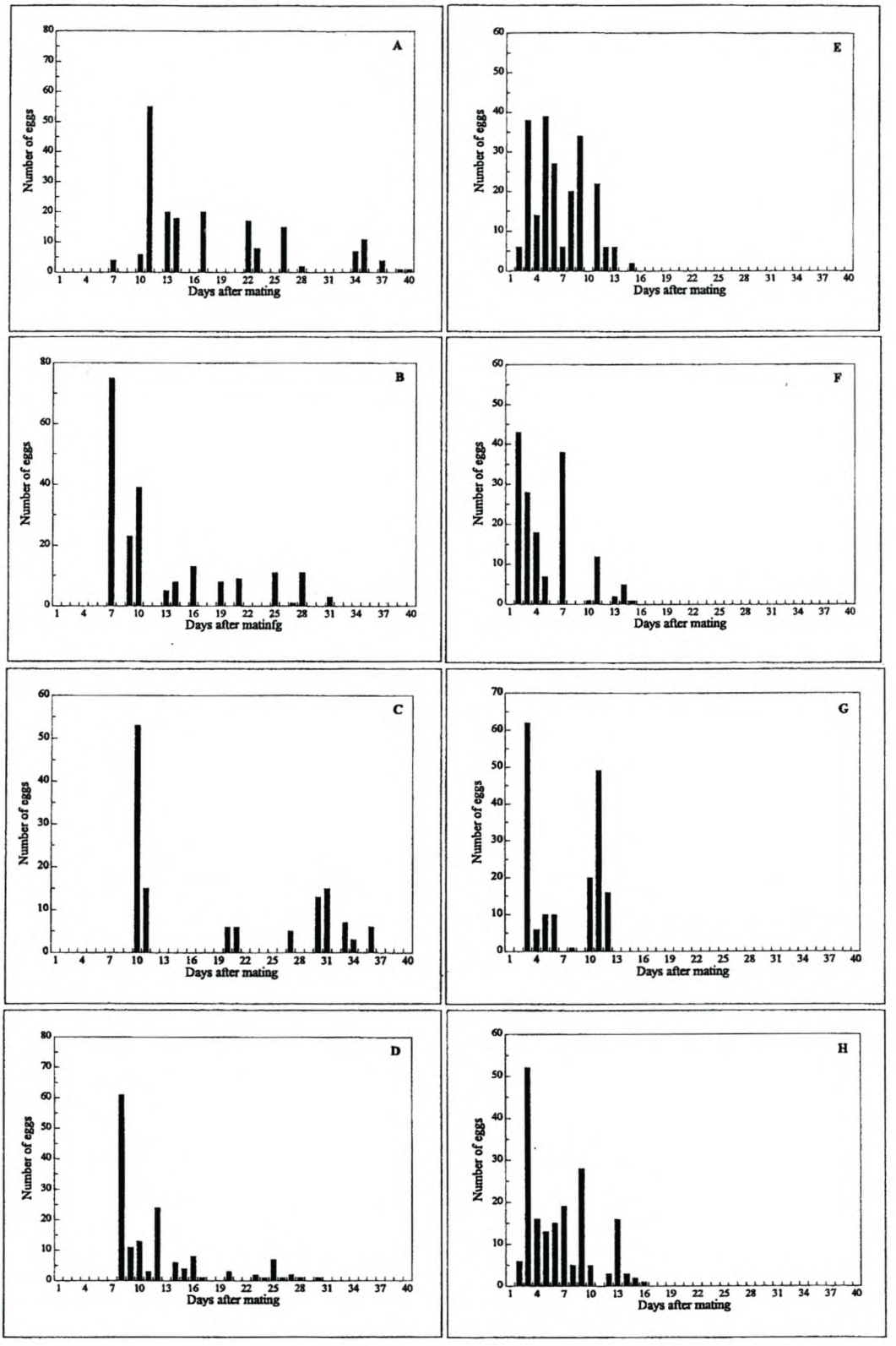

Fig.6. Daily oviposition of four *Cydia pomonella* moths each confined individually in oviposition cages at a constant temperature of 15°C (A,B,C,D) and 21°C (E,F,G,H).

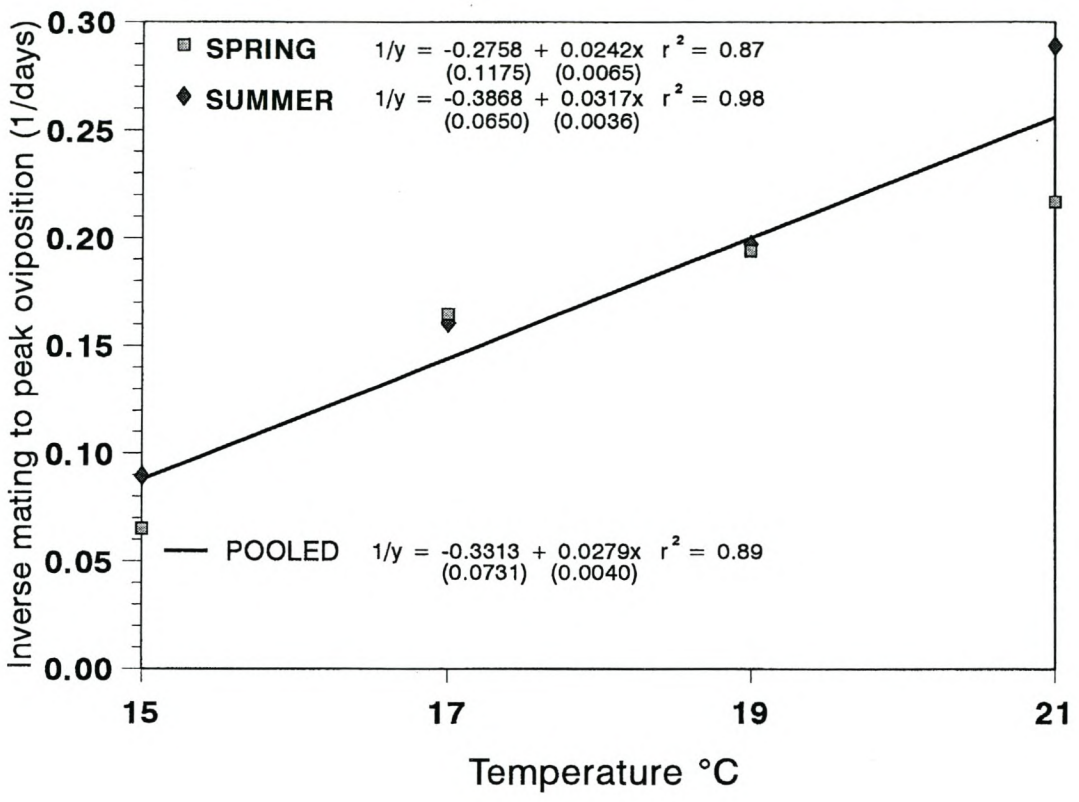

Fig. 7. Relationship between temperature and the inverse of the mean number of days after mating to peak oviposition of *Cydia pomonella* of the spring and summer generations (Standard error given in parenthesis).

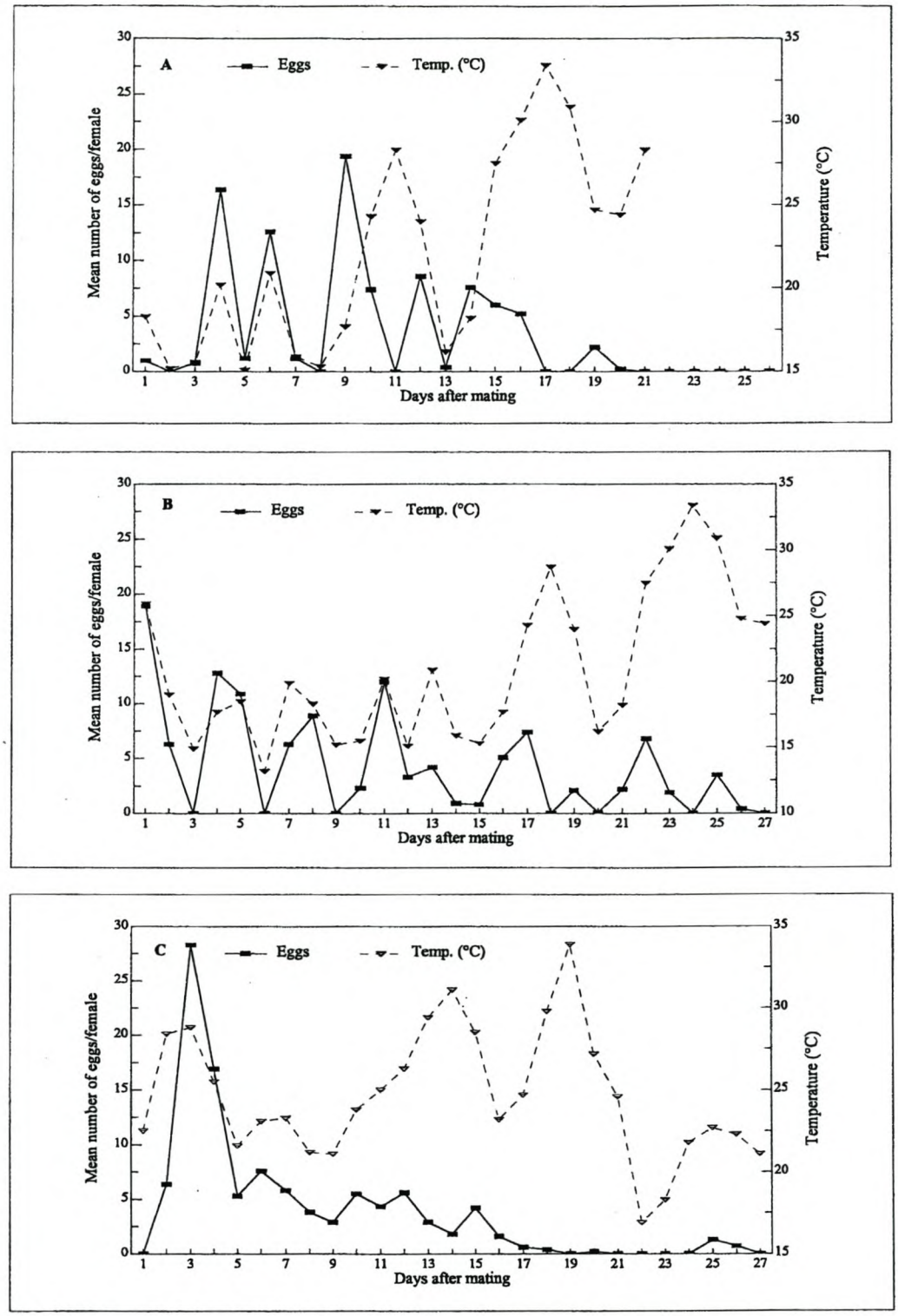

Fig. 8. Mean daily oviposition of *Cydia pomonella* of the spring generation at fluctuating temperatures. Mating occurred on (A) 18 October , (B) 26 October and (C) 18 November 1988.

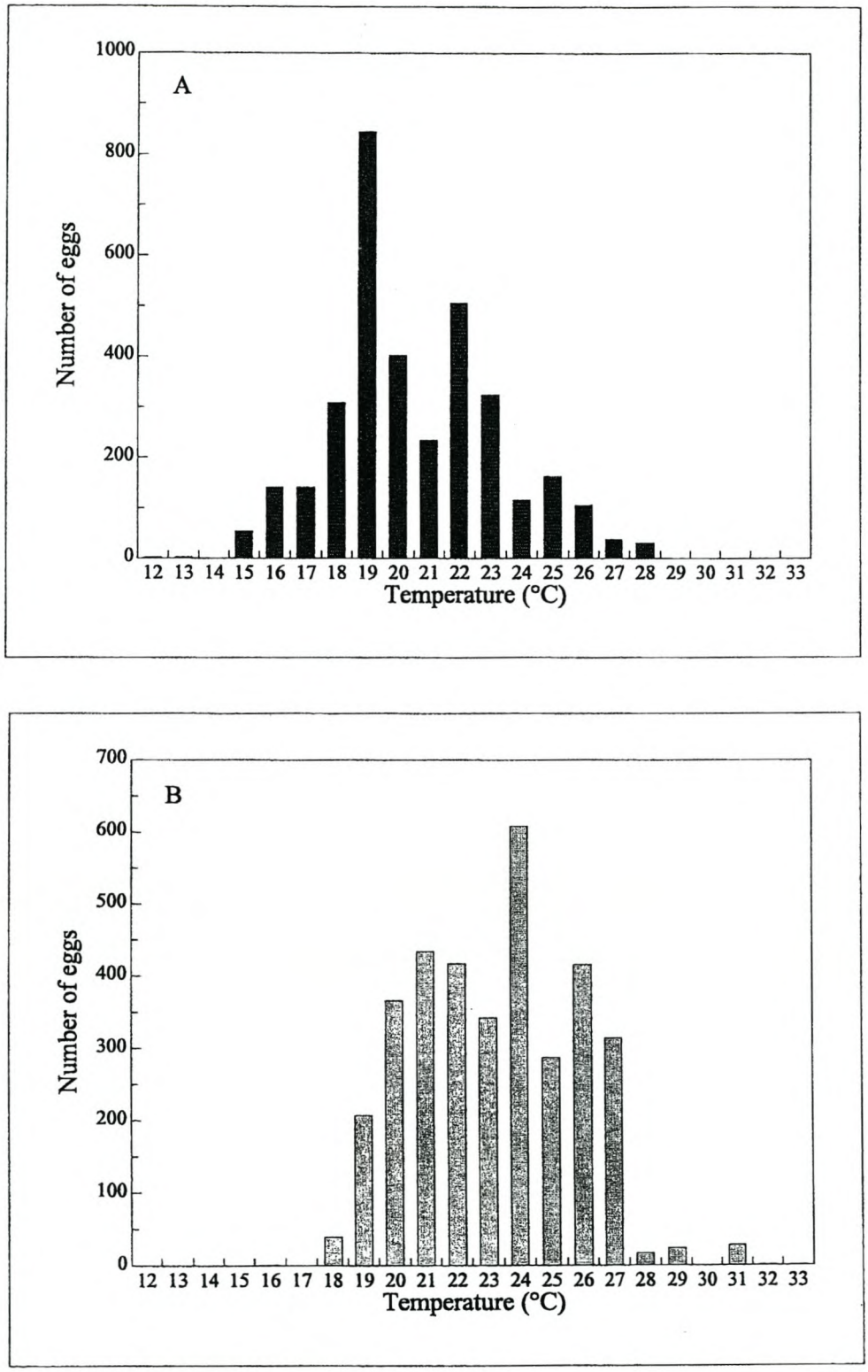

Fig. 9. Oviposition of *Cydia pomonella* of the (A) spring (n = 29) and (B) summer (n = 40) generations in relation to fluctuating temperatures.

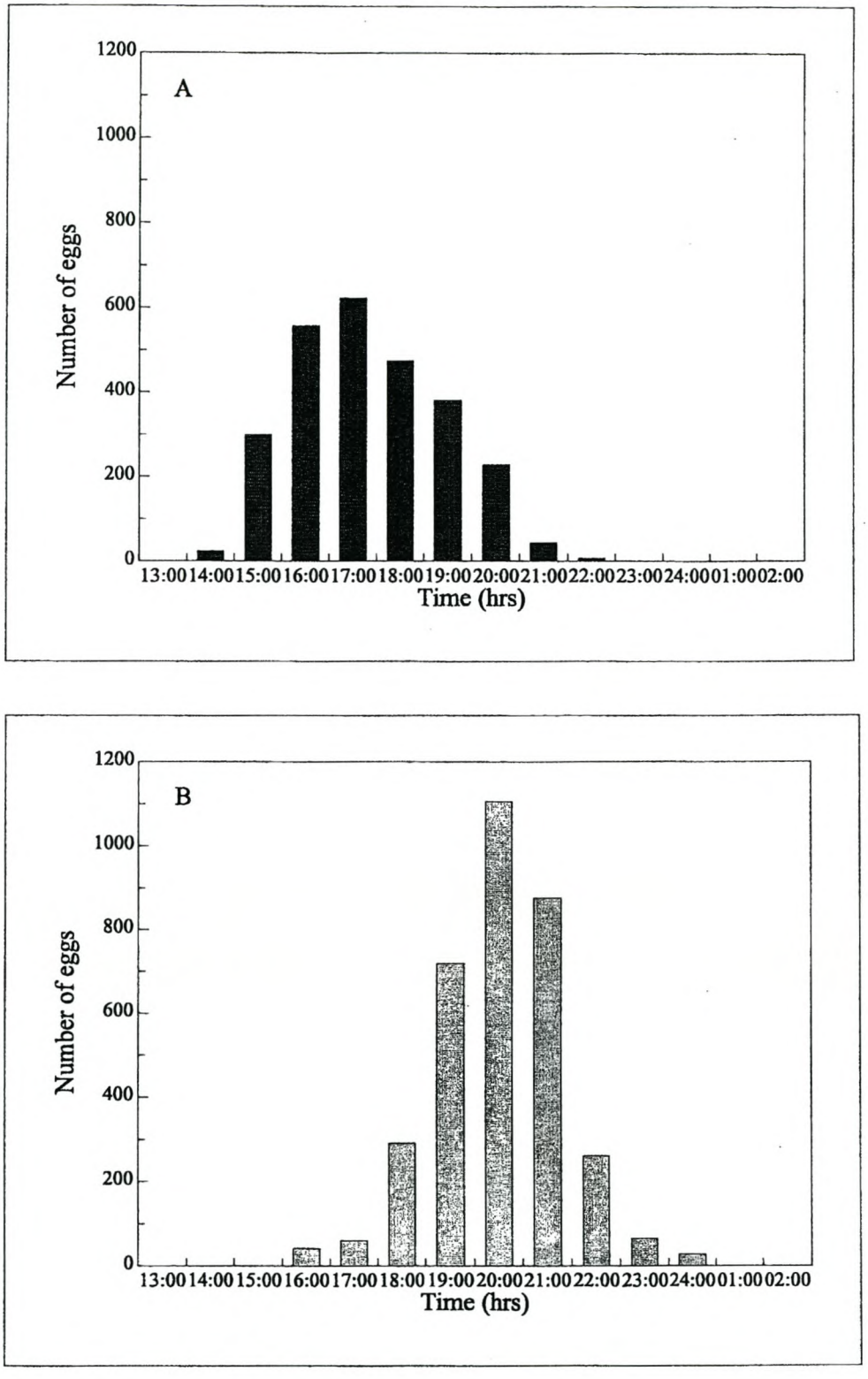

Fig. 10. Oviposition of *Cydia pomonella* of the (A) spring (n = 29) and (B) summer (n =40) generations recorded hourly at fluctuating temperatures.

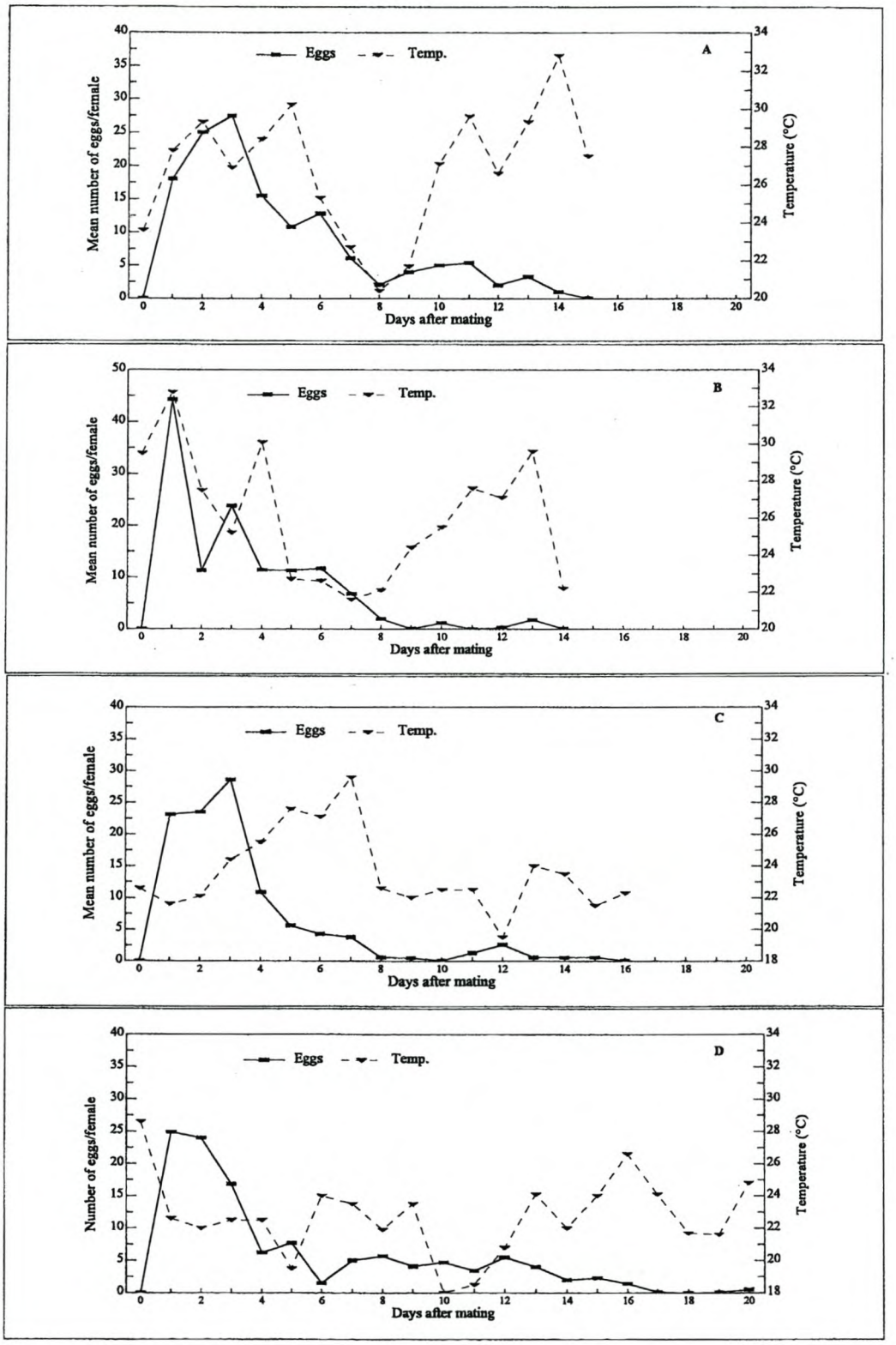

Fig. 11. Mean daily oviposition of *Cydia pomonella* of the summer generations at fluctuating temperatures. Mating occurred on (A) 24 January, (B) 6 February, (C) 12 February and (D) 19 February 1989.

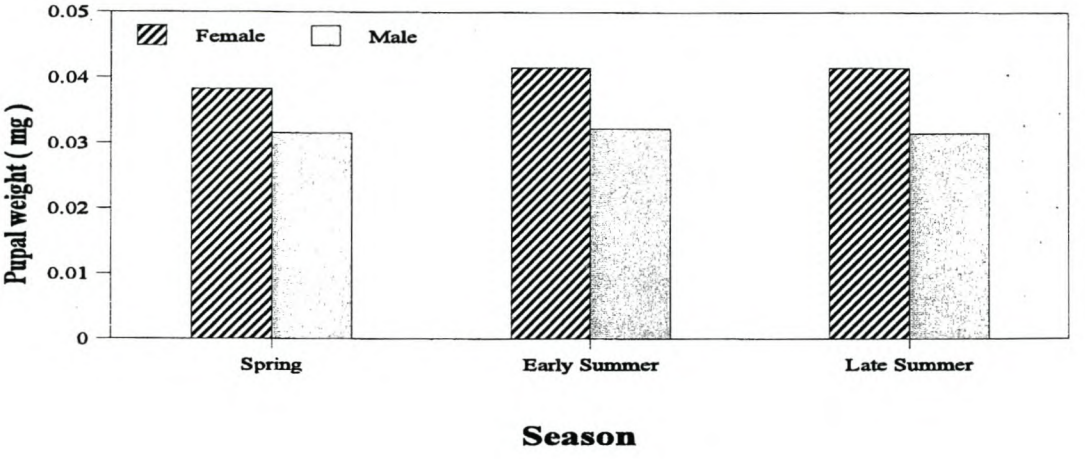

Fig. 12. Mean pupal weights (mg) of male and female pupa of *Cydia pomonella* of the spring, early summer and late summer generations.

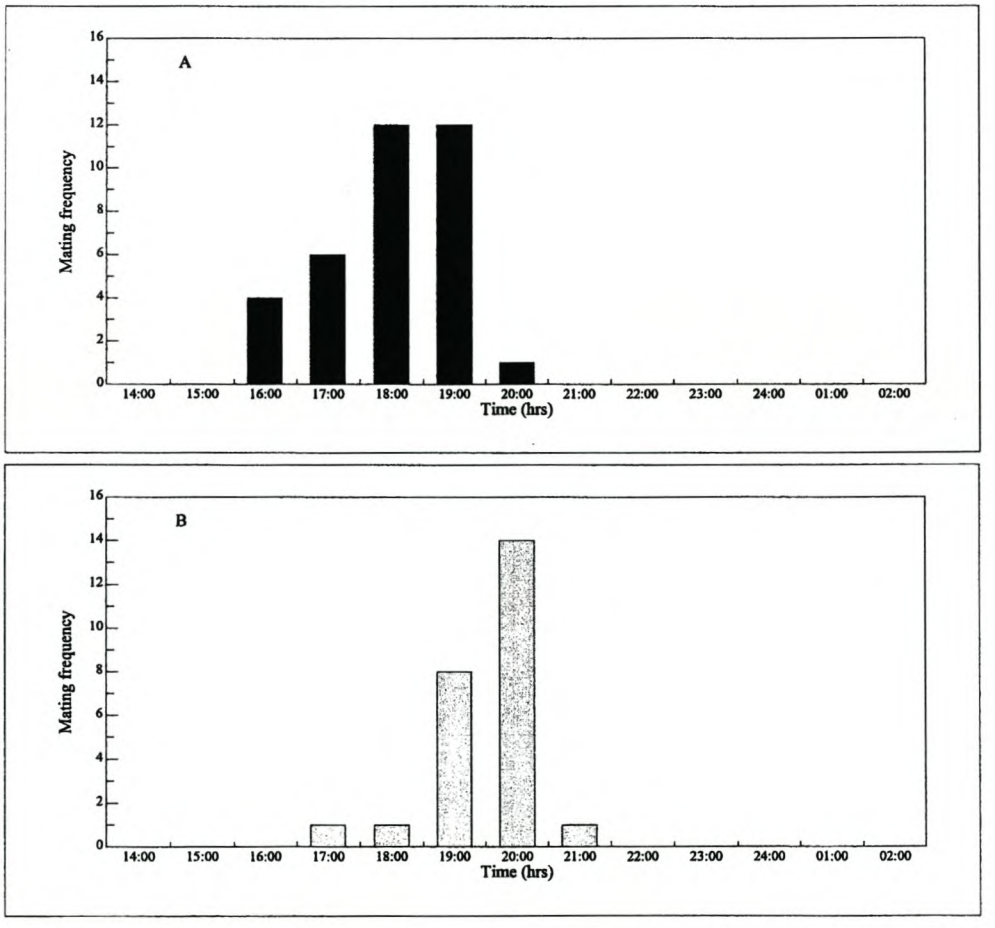

Fig. 13. Time of mating of *Cydia pomonella* of the spring generation in (A) October and (B) November at fluctuating temperatures.

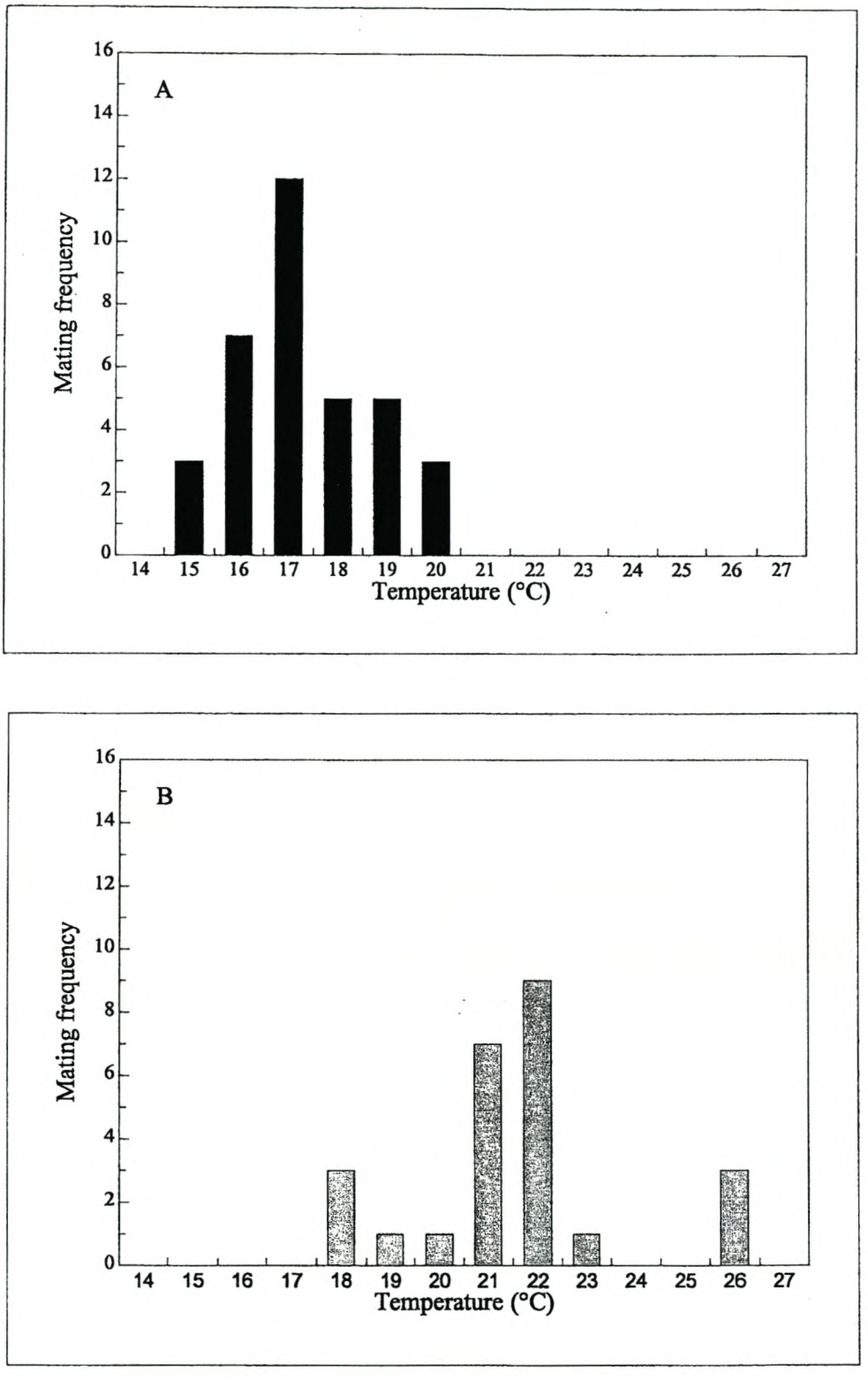

Fig. 14. Mating of *Cydia pomonella* adults of the spring generation in (A) October and (B) November in relation to fluctuating temperatures.

3. FECUNDITY OF THE SPRING AND SUMMER ADULTS AND MORTALITY OF EMBRYONIC AND IMMATURE STAGES OF CODLING MOTH UNDER FIELD CONDITIONS

ABSTRACT

Fecundity of the spring and summer adults and mortality of the egg, larval and pupal stages of codling moth, *Cydia pomonella* (L), obtained in sleeve cages in the orchard, are presented. There was no difference between the overall fecundity of the spring (135.2 eggs/female) and summer (159.3 eggs/female) moths. During the first third of October spring moths produced significantly fewer eggs than in November. Egg mortality in spring was 8.2 % while in summer it was 21.2 %. The increase in egg mortality during summer was due to the egg parasitoid, *Trichogramma luteum* Girault. During spring and summer mortality due to nonviable and viable but unhatched eggs was less than 5 %. In the absence of entomophagous insects the failure of 1st instar larvae to penetrate the fruit ranged from 4.9 to 19.5 %. The mortality of larvae from egg hatch to emergence from the fruit ranged from 29.7 to 43.8 %. Mortality of 5th instar larvae in cocoons spun in corrugated cardboard after emerging from the fruit was low, ranging from 0 to 8.7 %, while pupal mortality ranged from 0 to 3.5 %. The mean number of diapausing larvae on large 27-year old Golden Delicious and Granny Smith trees was 13.9 and 5.7 respectively. On 7-year old Golden Delicious and Granny Smith trees the mean number of overwintering larvae per tree was 0.5 and 2.0 respectively.

3.1 INTRODUCTION

Myburgh (1980) referred to the infestation potential of codling moth in South Africa as being one of the highest in the world. The high infestation potential was attributed to codling moth having three successive moth flights in a season extending over a period of eight months. This study has already shown that under very favourable climatic conditions four successive moth flights can take place in South African pome fruit orchards (Chapter 4). A high infestation potential may also be influenced by low natural mortality factors in the egg and larval stages. Although studies on natural mortality have been undertaken in other pome fruit production areas of the world (Summerland & Steiner 1943; MacLellan 1962; Geier 1963, 1964; Wood 1965; Ferro *et al.* 1976) similar studies have not been

undertaken in South Africa. It is probable that the natural mortalty of codling moth in South African pome fruit orchards differs from other pome fruit production areas of the world. This may account for the difficulty of controlling codling moth in South African pome fruit orchards.

For the development and implementation of an effective pest management programme for codling moth it is essential that a thorough understanding of the biology of the pest is obtained, including studies on the natural mortality of codling moth and those stages most vulnerable to natural mortality. The object of this study was therefore to obtain information on the fecundity of the spring and summer moths and mortality of the embryonic and immature stages of codling moth. The studies were undertaken in an unsprayed apple orchard to obtain fecundity and mortality parameters under field conditions. As the number of cocooning sites are considered to have an impact on the population dynamics of codling moth (Ferro *et al.* 1975) observations on the number of cocooning sites on young and old trees are also included, as well as the site of larval entry into the fruit of the spring and summer generations.

3.2 MATERIAL AND METHODS

3.2.1 Study sites

The fecundity and mortality studies were undertaken on the Elgin Experiment Farm between the 1986/87 and 1988/89 seasons. Studies on the overwintering cocooning sites on old and young apple trees were determined on the Elgin and Bellvue Experiment Farms, Elgin respectively. These orchards are described in the material and methods of Chapter 1.

3.2.2 Fecundity and egg mortality

Golden Delicious (GD) branches were enclosed shortly after full bloom with nylon netting sleeve cages with a mesh diameter of 2 mm. Branches were selected from inside the tree to provide the caged moths with as much shade as possible during the day. One female and two males that had emerged the previous night were introduced into each sleeve cage. Two to three weeks after introducing the moths into the cages the branches were removed from the trees, brought back to the laboratory and inspected for eggs. Eggs found were categorized as hatched, alive and dead. The

unhatched eggs were placed in open containers with moist cotton wool and maintained in a laboratory at 22°C ± 3°C and a RH of 70 % ± 10 %. The eggs were inspected every third day until no further egg hatch took place. Eggs that remained unhatched were categorized as infertile, parasitised or fertile but unhatched.

Studies were undertaken with moths from the spring and summer flights. Spring generation moths (early September to late November) originated from fifth instar larvae collected weekly from corrugated cardboard bands placed around the trunk and branches of Granny Smith (GS) trees the previous season. The diapausing larvae were kept in two cylindrical gauze cages suspended from branches in the orchard throughout the summer and winter months. The summer generation moths originated from mature larvae leaving the fruit in December through to February. During the three year study period 80 spring and 76 summer female moths were used for the fecundity studies (Table 1).

During the 1988/89 season, fecundity and egg mortality studies were undertaken between 3 October and 18 November 1988. Seven groups, consisting of 3 to 9 female moths per group, were used for these fecundity studies. To determine whether there was an increase in the number of eggs per female from the beginning of October to the end of November this period was divided into an early-, mid-and late-October and November. (Table 3). The data were subjected to an analysis of variance and the oviposition means from each period compared using Student's t-LSD at the 5 % significant level to compare treatment means. To augment the information on egg mortality the egg mortalities obtained during the ovipostion studies undertaken under fluctuating temperature in an insectary were included (Chapter 2).

3.2.3 Larval and pupal mortality

To determine 1st instar mortality (failure to penetrate the apple) and larval mortality from egg hatch to 5th instar emergence from the fruit, Golden Delicious (GD) branches 27 to 46 cm in length, were enclosed with gauze sleeve-cages shortly after full bloom. During the 1986/87 and 1987/1988 seasons 82 and 80 branches were enclosed respectively. During each season half the number of branches were used in two periods, between November and December and January and February. Prior to the branches being enclosed the fruit and leaves were inspected for live eggs which were

removed if found. The branches remained enclosed in the sleeve cages for the duration of the trial. In each sleeve-cage 10 to 11 eggs on individual pieces of wax paper, were stapled to leaves in close proximity to a fruit. Prior to the eggs being stapled to the leaves the interior of the bags and fruit were again inspected for larvae or signs of fruit infestation. Any larvae or infested fruit found in the sleeve cages were removed. After five days half the number of branches were randomly removed from the trees and brought back to the laboratory. All the fruit in each cage were carefully dissected and microscopically inspected for larvae. Egg hatch was determined for each branch removed from the orchard and for the caged branches remaining in the orchard. Corrugated cardboard was placed inside each bag remaining in the orchard to serve as cocooning sites for mature larvae emerging from the apples before the branches were removed.

Three weeks after the eggs were stapled to the leaves, the branches that were left in the orchard were removed from the trees and brought back to the laboratory for inspection. The fruit was dissected and inspected for the presence of larvae. Each fruit containing an immature larva was placed in a plastic container with corrugated cardboard, sealed with a gauze cloth and kept under fluctuating temperatures in an open insectary. The containers were inspected at regular intervals for larval and moth emergence. The larvae that had entered diapause were inspected the following spring to determine moth emergence and mortality in the larval and pupal stages. During the 1989/90 season the larval and pupal mortality in the cardboard bands was not determined.

During the 1998/99 season the procedure was changed to reduce the incidence of more than one larvae entering a fruit. One hundred individual fruit spurs were enclosed in gauze sleeve cages shortly after full bloom. The fruit spurs were inspected for eggs which were removed if found. Two eggs, each on an individual piece of wax paper, were stapled to the leaves of each fruit spur. Thereafter the procedure was the same as during the 1987/88 and 1989/90 seasons. During the 1988/89 and 1998/90 the point of entry of the larvae into the fruit was also recorded. In addition studies were undertaken during October and February of the 1990/91 season to determine the point of entry into immature fruit.

3.2.4 Number of diapausing larvae on old and young trees

On the study site on the Elgin Experiment Farm 10 GD and 9 GS trees were meticulously searched for cocoons containing overwintering larvae before spring moth emergence. Similarly on the study site on the Bellvue Experiment Farm 20 trees of each cultivar were searched for overwintering larvae. All lose bark, crevice, torn branches, woolly apple aphid damage sites and pruning wounds were searched for live larvae from the soil surface to the top of the trees. Each overwintering site, diameter of branch and distance (cm) from the soil surface was recorded. To monitor the possible emergence of adults of the spring generation from the soil, 10 metal ground traps were placed under the trees in the Bellvue orchard, approximately 30 cm from the tree trunk. Each trap was made from galvanized sheeting in the form of a box 55 cm square. A 38 cm square hole was cut out of the roof of the trap. The opening was covered with fly-screen gauze to allow rain through to the soil beneath the trap. One trap was also placed under a tree and the traps were randomly distributed throughout the orchard. Without disturbing the soil the vegetation within the confines of the trap site was cut to ground level and a thin film of white building sand spread over the soil surface to facilitate the inspection of the boxes for codling moth adults. A sticky bottom of a pheromone trap, on which a pheromone lure had been placed, was placed in each ground trap.

3.3 RESULTS

3.3.1 Fecundity and egg mortality

Details of the mean fecundity of the spring and summer moths, percentage egg hatch and mortality are shown in Table 1. Between 1986 and 1988 the mean fecundity of the spring generation moths varied from a mean of 107.7 to 170.0 eggs per female with an overall mean fecundity of 135.2 eggs per female. The lower mean fecundity obtained for the spring moths during the 1988 season is probably due to fecundity trials commencing at the beginning of October , while in 1986 and 1987 fecundity trials were undertaken towards the end of October and from mid-November to beginning of December respectively. During the 1988 spring fecundity trials there was a significant difference in the mean number of eggs per female during the first third of October compared to the mid-, late-October and November periods (Tables 2-3).

During the spring period a high percentage egg hatch was recorded with an overall mean of 91.8 %. The main contributions to egg mortality were the egg parasitoid, *Trichogramma luteum*, particularly in the summer months, and viable but unhatched eggs. The mesh of the netting was large enough to allow the parasitoid to enter the sleeve-cages. A low percentage of eggs was non-viable and there was a low mortality due to unknown causes. Most of the eggs that died from unknown causes turned brown or were covered with fungus. It is unknown whether the eggs died from the fungus or were already dead prior to the growth of the fungus. Many of the brown coloured eggs had partially developed larvae in them suggesting that these eggs were viable but for some reason did not hatch.

The mean fecundity of the summer generation was more consistent varying from 154.3 to 162.1 eggs per female, with an overall mean fecundity of 159.3. Lower egg hatch was recorded during the summer months (78.8 %) than during the spring period (91.8 %). This was mainly due to increased egg parasitism during the summer months. However, percentage mortality due to eggs being non-viable, viable but unhatched and mortality unknown was very similar to that of the spring moths.

The mean fecundity of moths from the spring (92.6) and summer (121.2) generations, obtained from studies done in small nylon netting cages at fluctuating temperatures in an open insectary (Chapter 2, Fig. 1), yielded lower mean fecundities and higher mortalities than the studies undertaken in the orchard (Table 4). In these studies mortality due to parasitoids was excluded.

3.3.2 Larval and pupal mortalities

Details of larval and pupal mortalities are shown in Tables 5-6. During the three year study period 1st instar mortality during the November/December period varied from 8.8 % to 19.5 % with an overall average mortality for the three years of 12.2 % (Table 5). During the 1988/89 and 1989/90 seasons 70 % and 73 % 1st instar larvae respectively entered the fruit through the calyx. First instar mortality during the summer months varied from 4.9 % to 14.5 % in the 1987/88 and 1989/90 seasons respectively, with an overall average mortality of 8.4 % (Table 6). A high percentage of these larvae (70 %) entered the fruit through the side. During the November/December period larval mortality from the egg hatch to 5th instar larval emergence from the fruit varied from 29.7 % to 37.9 % with an overall mortality of 33.3 %. During the summer months larval mortality from egg hatch to 5th instar

larval emergence from the fruit varied from 32.5 % to 43.8 % with an overall mean mortality of 38.6 %.

The percentage of larval mortality after emerging from the fruit and spinning cocoons in the corrugated cardboard bands was very low. The mortality of 5th instar larvae originating from larvae entering fruit during the November/December period was very low varing from 0 % to 2.8 % with an overall mean of 1.8 %, while during the summer months the overall mortality of 5th instar larvae was 8.3 %. Pupal mortality was also very low during both periods, the overall pupal mortality during November/December was 3.2 %, while during the January/February period it was 0 %.

3.3.3 Number of diapausing larvae on old and young trees

Details of the mean number of cocoons found containing live larvae on old and young GD and GS trees in spring are shown in Table 7. On the large GD trees on the Elgin Experiment Farm there was a mean of 13.9 larvae per tree, while on the GS cultivar a mean of 5.7 larvae per tree was observed. The maximum number of larvae found on a GD tree was 24, while on a GS tree the maximum was 11. On both cultivars the majority of the larvae were located in old prunning cuts that were in the process of decay and on prunning wounds that had not been properly sealed or cut. Although most of the larvae (74.1%) were found in cocooning sites within 1.4 m of the soil surface, some diapausing larvae were located in pruning wounds 4 m above the soil surface. On the 7-year old trees on the Bellvue study site the mean number of larvae per GD and GS tree was 0.5 and 2.0 respectively. The maximum number of larvae found on a GD and GS tree was 3 and 10 respectively. On two occasions 8 and 9 larvae were found on GS trees in sites where branches had broken under the weight of the apples. If these two groups of larvae were excluded the mean number of larvae per tree decreased to 1.1. On the GD trees most of the larvae were located under bark and in prunning wounds.

3.4 DISCUSSION

Data from Ferro *et al.* (1975), and other researchers' observations on fecundity of spring and summer moths and mortality of the embryonic and immature stages are presented in Tables 8-11 for comparative purposes. More recent observations on fecundity and mortality of each stage by other

researchers have also been included.

3.4.1 Fecundity and egg mortality

The overall number of eggs per female of moths of the spring generation (135.2) was higher than reported by other researchers done under field conditions (Geier 1963; Wearing 1971; Ferro *et al.* 1975; Trottier & Hagely 1979) (Table 8). The mean fecundity, however, of the moths introduced into the sleeve cages from 3 October to 18 November 1988 (Table 1) was 107.7. When this observation period was divided into four periods and subjected to an analysis of variance the analysis indicated some evidence of significant differences (P = 0.0571). Comparison of the means with a pair-wise t-test at P = 0.05 % indicated that significantly fewer eggs were produced per female in the first third of October (63.4) compared to November (134.4) (Table 3). The lower fecundity obtained for the first period is attributed to lower evening temperatures in the beginning of October. The mean fecundity of spring moths obtained from studies done in small nylon netting cages at fluctuating temperatures in an open insectary yielded a mean fecundity of 92.6 eggs/female (Table 4). Both these studies were done at a similar time of the year, from beginning of October to mid-November. Hagley (1973) observed a similar trend, with moths emerging during the first 14 days in spring laying fewer eggs than those emerging during the following 7-day period (Table 8). Although a relatively low fecundity was recorded for the moths placed in sleeve cages in the beginning to middle of October, more than 50 % of the spring moth population emerges after approximately 20 October when temperatures are more favourable for codling moth reproduction and oviposition.

The fecundity of the summer generation moths ranged from 154.3 to 162.1 eggs/female with an overall mean of 159.3eggs/female , which is considerably higher than the findings of other researchers (Table 8) and the data obtained at fluctuating temperatures in an open insectary (Chapter 2, Fig. 1). There was no significant difference between the number of eggs per female for spring moths (135.2) and that for summer moths (159.3) (t_{154} = 0.2199, P = 0.8352). The data suggests that under favourable climatic conditions the fecundity of the spring moths, particularly after approximately 50 % moth emergence of the spring population, is comparable to that of the summer moths. The high fecundity obtained for the spring and summer moths may explain why codling moth in South Africa is considered to have one of the highest biotic potentials in the world (Myburgh 1980).

In this study and those done under fluctuating temperatures in the insectary (Chapter 2) the number of non-viable eggs laid by the spring and summer generation moths was considerable lower than that obtained by Hathaway *et al.* (1971), Hagley (1972) and Ferro *et al.* (1975) (Table 9). All these studies excluded mortality due to entomophagous insects. However, only the study of Ferro *et al.* 1975 was done under field conditions. In a field study where entomophagous insects were not present or their numbers very low, Wood (1965) observed very low levels of egg mortality, ranging from 4.7 to 6.9 % (Table 9), mortality being attributed to dislodgement due to rain or wind and failure to hatch. MacLellan (1962), who observed the development of 2708 eggs oviposited on fruit spurs by feral moths, recorded an egg mortality of 16.7 %. Of these eggs 14.4 % were preyed on and only 2.3 % failed to emerge, no reason being given for the failure of these eggs to emerge. Summerland & Steiner (1943) reported a 5 % inviability, 7 % disappearance and 32 % parasitism of eggs laid by feral females, while Westigard *et al.* (1976) reported a mortality of 24 % of which 9.7 % was due to infertility or sucking predators.

In the present study egg mortality would have been much lower if the egg parasitoid, *Trichogramma luteum*, was excluded. During the first generation period parasitism was only 3.5 %, while during the summer moths egg parasitism increased to 15.9 %. Nel (1942) reported parasitism by the egg parasitoid of up to 90 % after January in unsprayed orchards. To prevent the egg parasitism from taking place a sleeve bag would have had to be used with a very fine weave and this may have affected the environment within the bag. When sleeve cages were used with a very fine weave, as in the case of the larval mortality studies, there tended to be an increase in woolly apple aphid, *Eriosoma lanigerum* (Hausm.), trapped in the sleeve cages when the branches were enclosed. This resulted in a decline in the leaf quality and leaves turning yellow followed by premature leaf drop. The percentage of non-viable eggs was low in the sleeve cages compared to the studies undertaken in the insectary. A further problem encountered with the sleeve-cage studies was that some eggs at different stages of development partially overlapped one another. In such cases the first larva to emerge often chewed through part of the overlapping egg, resulting in the damaged egg drying out and death of the developing larva. This increased the mortality of eggs in the category of viable but unhatched. However, despite the limitations of the sleeve-cage studies, the percentage of eggs viable but unhatched and dead due to unknown causes was lower than those recorded for the fecundity studies in the insectary (Table 4). Towards the end of the season there was a decrease in leaf quality

with leaves turning yellow and patches of the leaves turning brown and drying out. This may account for the increase in percentage viable but unhatched eggs during the summer fecundity trials in 1989.

3.4.2 Larval and pupal mortalities

The overall percentage mortality of 1st instar codling moth larvae during November/December (12.2 %) and January/February (8.4 %) was very low in comparison to the findings of other researchers except for Wood (1965) (Table 2). This researcher reported a 1st instar mortality of 10 % before entry into the fruit. Although predation was not observed, a mite (*Anystis agilis* Banks) considered to be a predator of 1st instar codling moth larvae (MacLellan 1962), was observed to be present. This In the present study each larval entry point was microscopically examined to ensure that the larva had successfully penetrated the apple and that the entry point was not an abortive entry point. In the studies undertaken by Hall (1934), MacLellan (1962) and Ferro *et al.* (1975), each "hit" represented a successful entry point. However, it is possible that larvae may have eaten into the apple at more than one entry site and also penetrated through the calyx of the fruit, particularly when the fruit is small. A high percentage of 1st instar larvae entered the fruit through the calyx in November/December (70-80 %) and even in the summer months (30 %). The larvae that enter through the calyx can only be detected much later. By not dissecting and microscopically inspecting the fruit an inflated mortality of 1st instar larvae may have been obtained. Ferro *et al.* (1975) stated that the 1st instar mortality of 65 % may have been higher than under field conditions. During the 1987/88 and 1988/89 seasons it was noted a number of fruit had more than one entry point. Although this may not have impacted on 1st instar mortality it may have resulted in increased competition and mortality of larvae within the fruit.

The most important climatic factor impacting on 1st instar survival shortly after penetrating the fruit is rainfall. Hagley (1972) showed that 1st instar mortality was positively correlated with total rainfall, the larva drowning when the entry hole and tunnels just below the surface become waterlogged. Larvae that entered the fruit through the calyx opening may also drown when the calyx cup becomes filled with water which does not evaporate during cool periods. Knight (1998) reported a high incidence of shallow damage in orchards treated with overhead irrigation, suggesting that larvae drowned or were washed off the fruit after limited feeding. The high moisture content in the calyx

cup or entry tunnel may also predispose the larvae to fungal and viral infections. Puttman (1963) states that warm, dry conditions and seasons, as exist in South African apple producing areas, encourage higher infestations of codling moth than cool, moist ones.

The overall larval mortality from egg hatch to emergence from the fruit during the November/December period (33.3 %) and the summer months of January and February (38.6%) was similar to the mean percentage mortality obtained by Ferro *et al.* (1975) early in the season (34.6). Ferro *et al.* (1975) stated that the higher mortality observed later in the summer (52 %) was due to greater competition within the apples. Only during the 1989/90 season was mortality later in the season (43.8 %) higher than that obtained earlier in the season. The reason for the increase in mortality during the January/February period is unknown.

Of the larvae that left the fruit and spun cocoons in the corrugated cardboard bands the overall mortality was lower early in the season(1.8 %) compared to later in the season (8.3 %). In this study the percentage 5th instar larval mortality after leaving the fruit was determined under conditions that excluded attack by entomophagous insects. The studies undertaken by other researchers did not exclude attack by entomophagous insects (Table 11). In three of the studies mortality due to the parasitoid, *Ascogaster quadridentata* Wesmael varied between between 5.3 % and 32 % (Boyce 1943; Garlick 1948; Ferro *et al.* 1975). MacLellan (1960) recorded a mortality of 94 % of larvae spinning cocoons on the ground. The observations of the other researchers have shown larval parasitism to be an important parameter with respect to larval mortality. Ferro *et al.* (1975) estimated 5th instar mortality to be about 30 % in unsprayed orchards. In earlier studies undertaken in South Africa (Nel 1942), parasitism of the larval stage was low, varing from 5.3 % to 12.2 % during a three year study period in an unsprayed pear orchard (Table 11). Once the larvae had entered the corrugated cardboard and pupated, pupal mortality was low, not exceeding 3.5 % for the earlier and later part of the season. This percentage is very similar to that obtained by Ferro *et al.* (1975). Under commercial apple production, where moth populations are very low, it is unlikely that larval parasitoids contribute to the control of codling moth.

3.4.3 Number of diapausing larvae on old and young trees

The mean number of overwintering larvae on the GD trees was significantly greater than that on GS trees. This suggests that mature GD trees provided a greater number of cocoon sites than GS trees. The reason for the higher number of cocoon sites on the GD trees is unknown but it would appear that the wood of the GD tree is softer than that of the GS tree. This observation was noted when digging into old pruning wounds and where branches had broken. Many of the older prunning wounds on the GD trees appeared to be in a more advanced stage of decay than those on GS trees. The GS trees also appeared to have less loose bark and greater areas of smooth bark, resulting in fewer overwintering sites. Wearing & Skilling (1975) concluded that the upper limit for the number of cocoons per tree on young trees of 2.5 to 3.6 m in height and with a trunk circumference of 17 to 29 cm was a mean of 5 cocoons. This was reached when a density of 12 larvae were released per tree. However, in commercial orchards, where the trees are mature and codling moth is under an effective integrated control programme, it is unlikely that competition for cocooning sites will limit the overwintering population. The high proportion of diapausing larvae found in pruning wounds indicates that pruning wounds are an important overwintering site. Therefore, proper training and pruning of the tree should take place from the time of planting. Large-scale corrective pruning at a late stage increases the number of large pruning wounds and overwintering sites. It is important to obtain a very smooth pruning cut and seal the wound with sealant. The wood of a well sealed pruning wound, particularly on a GD tree, will be less prone to decomposition and the sealant will give the wood sufficient time to heal before weathering away. Once a cocooning site has been established in a pruning wound, the site can be exploited by successive generations of codling moth.

Fecundity and mortality studies have indicated that codling moth in South Africa probably has higher biotic potential than most other populations. The high fecundity of codling moth, particularly in the spring moths, and the relatively low mortality of the embryonic and immature stages of codling moth places a severe strain on any programme that relies exclusively on insecticides. Only a thorough understanding of those parameters that affect the population dynamics of codling moth will lead to the development of more sustainable management practices and a more holistic approach to codling moth management.

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Table 1. Fecundity of spring and summer moths and mortality of *Cydia pomonella* eggs from caged-in branch studies in an unsprayed apple orchard during the 1986/87 and 1988/89 seasons.

Period	n	Mean eggs/ female (eggs ± SE)	Percentage eggs:					Total egg mortality (%)
			Hatched	Non-viable	Viable but unhatched	Unknown	Parasitized	
Spring moths								
30 October 1986	10	170.0 ± 25.18	94.0	1.8	4.1	0	0.1	6.0
11 Nov - 4 Dec 1987	29	162.1 ± 14.12	88.6	0.9	4.5	0.8	5.2	11.4
3 Oct - Nov 1988	41	107.7 ± 9.75	94.5	0.6	2.1	0.2	2.5	5.5
Overall	80	135.2 ± 8.33	91.8	0.9	3.3	0.5	3.5	8.2
Summer moths								
31 January 1987	10	162.1 ± 17.50	85.2	1.2	4.2	1.0	8.4	14.8
20 Jan - 24 Feb 1988	30	154.3 ± 7.70	84.1	1.3	8.9	0.9	4.8	15.9
19 Jan - 16 Mar 1989	36	158.8 ± 10.90	72.6	0.2	23.7	0.9	2.6	27.4
Overall	76	159.3 ± 6.34	78.8	0.7	3.7	0.9	15.9	21.2

Table 2. Results of the analysis of variance on mean number of eggs/per female of *Cydia pomonella* oviposited in early-, mid-,late-October and November.

Source	DF	Mean square	P
Period	3	9449.33478	0.0571
Error	37	3450.4336	0.0571
Total corrected	40		

Table 3. Comparison of the oviposition means of *Cydia pomonella* from each of four periods with a pair-wise t-test using the harmonic mean.

Period	Date moths placed in sleeve cages	n	Mean number of eggs/female
1. Early -October	3 Ocober 10 October	9	63.4 b*
2. Mid-October	17 October 24 October	8	106.4 ab
3. Late-October	31 October	8	109.0 ab
4. November	11 November 18 November	15	134.4 a

*Means followed by the same letter (s) do not differ significantly at P = 0.05
LSD (P = 0.05) = 54.143

Table 4. Fecundity of spring and summer moths and mortality of *Cydia pomonella* eggs from cage studies in an open insectarium under fluctuating temperatures during the 1988/89 season.

Period	n	Mean eggs/ female (eggs ± SE) [range]	Percentage eggs:				Total egg mortality (%)
			Hatched	Non-viable	Viable but unhatched	Unknown	
Spring moths 1 Oct - 18 Nov 1988	40	92.6	81.4	4.5	10.7	3.4	18.6
Summer moths 25 Jan - 19 Feb 1989	39	121.2	78.3	4.7	12.4	4.6	21.7

Table 5. Mean percentage mortality of 1st instar *Cydia pomonella* larvae, not entering the fruit during two periods of the 1987/88, 1988/89 and 1989/90 seasons.

Periods	No. of 1st larvae emerged from eggs stapled to leaves	Mean % mortality of 1st instar larvae ± SE
1987/88		
November - December	204	13.6 ± 2.61
January	196	14.5 ± 2.01
1988/89		
November - December	197	19.5 ± 3.55
January	178	11.2 ± 3.00
1989/90		
November	95	8.8 ± 3.01
December - January	99	4.9 ± 2.10

Table 6. Mean percentage mortality of *Cydia pomonella* larvae between egg hatch and 5th instar emergence from the fruit, and larval and pupal mortality in corrugated cardboard during two periods of the 1987/88, 1988/89 and 1989/90 seasons.

Periods	No. of 1st instar larvae emerged from eggs stapled to leaves	No. of 5th instar larvae emerged from fruit	Mean % larval mortality	Mean % larval mortality in cardboard bands	Mean % pupal mortality in cardboard bands
1987/88					
November -December	200	141	29.7 ± 3.30	2.8 ± 1.93	3.0 ± 1.42
January - February	197	134	32.5 ± 4.43	8.7 ± 3.37	0
1988/89					
November -December	189	120	37.9 ± 4.82	0.7 ± 0.7	3.5 ± 1.46
January - February	187	122	31.6 ± 3.73	7.9 ± 3.26	0
1989/90					
November -December	81	58	32.9 ± 5.11	0	0
December - February	96	57	43.8 ± 5.58	-	-

Table 7. Mean number of *Cydia pomonella* cocoons containing live larva on old and young Golden Delicious and Granny Smith trees in unsprayed orchards in spring and percentage larvae found in each overwintering site.

Cultivar	Mean number of Larva and pupa/ tree (± SE)	Percentage of larvae found in each overwintering site				
		Cracks	Under bark	Prunning sites	Woolly apple aphid damage	Torn/broken branches
Old trees						
Golden Delicious	13.9 ± 1.91	7.2	12.2	69.8	2.2	8.6
Granny Smith	5.7 ± 0.94	9.8	11.8	78.4	0	0
Young trees						
Golden Delicious	0.5 ± 0.2	0	50	40	10	0
Granny Smith	2.0 ± 0.61	0	38.5	17.9	0	43.6

Table 8. Fecundity of *Cydia pomonella* (From the present study and Ferro *et al.* 1975).

Researcher	Mean eggs/female		n	Range
Blomefield (Present study)				
Insectary				
Spring moths (1988)	92.6 ± 62.21		40	
Summer moths (1989)	121.2 ± 77.99		39	
Orchard				
Spring moths (1986-1988)	135.2 ± 75.56		80	
Summer moths (1987-1989)	159.3 ± 55.23		76	
Ferro *et al.* (1975)				
Native (1973)	42 ± 5.3		9	
(1974)	37 ± 3.9		4	
Lab. (1973)	53 ± 4.6		7	
(1974)	49 ± 3.9		4	
Deseo (1973)				
overwinter	16.8		108	
1st summer brood	83.3		130	
2nd summer brood	36.6		73	
Geier (1963)	44			8-80
Hagley (1972)	61 ± 59 (Oviposition period - 5 days) 236 ± 96 (Oviposition period - 14 days)			
Hagley (1973)	1-14 days oviposition period	15-21 days oviposition period		
1970	28 ± 10	59 ± 13		
1971	12 ± 6	47 ± 7		
1972	23 ± 8			
Hall (1929)				
overwinter	64 (Max. eggs = 234)			
1st summer brood	83 (Max. eggs = 208)			
Hathaway *et al.* (1971)				
lab. colony on immature apples	76.0			
Tadic (1957)	38 ± 22.7			
Trottier & Hagely (1979)				
Vinelands	9.7		174	
Meaford	32.9		81	
Wearing (1971)				
1967/68	44.9			9-116
1968/69	90.0			1-220
1969/70	47.0			0-182

Table 9. Percentage mortality of *Cydia pomonella* eggs (From the present study and Ferro *et al.* 1975).

Researcher	% mortality	Mortality attributed to:
Blomefield (Present study)		
Insectary		
Spring moths (1988)	81.4 (n = 3 702)	
Summer moths (1989)	78.3 (n = 4 851)	
Orchard		
Spring moths (1986-1988)	91.8 (n = 10 819)	
Summer moths (1987-1989)	78.8 (n = 12 104)	
Ferro *et al.*		non-viable
Native 1973	25 (n = 1879)	
1974	19 (n = 733)	
Lab. 1973	29 (n = 1845)	
1974	17 (n = 988)	
Ferro *et al.* Snake Orchard		
leafcluster + apples	x = 27.4 SD = 13.6 n = 7	parasitoid (*T. minutum*)
leafcluster + apples	x = 22.7 SD = 11.2 n = 7	predators, disease or nonviable
Total	x = 50.1	parasitoid + predator
Dolphin *et al.* (1972)	53 - 75	parasitoid (*T. minutum*)
	46 - 80	parasite (*T. cacoeciae*)
Hagley (1972)	12 - 62	non-hatched based on temperature and humidity
Hathaway et al. (19710	18 - 35	diet related
MacLellan (19620	14.4	Predators (4 mirid spp)
Nel (1942)	90	parasitoid (*Trichogramma luteum*)
Summerland & Steiner (1943)	32 - 43	parasitoid (*Trichogramma* sp.)
	19 - 23	predator (chrysopid larvaesp.)
Westigard *et al.* (1976)		
1970	20	*T. minutum*, shriveled and disappearance
1971	33	
Mean	26.5	
Wood (1965)		
Appleby	4.7 - 6.9	disappearance and failure to hatch
Maputa	11	disappearance and inviability
	14	parasitism
	1	predation

Table 10. Percentage mortality of *Cydia pomonella* 1st instar larvae (Ferro *et al.* 1975).

Researcher	% mortality	n	Mortality attributed to:
Ferro *et al.*[a]			
Native 1973	62 ± 9.9[b]	9	unknown[c]
1974	72 ± 8.8	4	
Lab. 1973	63 ± 11.0	7	
1974	63 ±11.6	4	
Hagley (1972)	11		rain
Hall (1934)	66		unknown[c]
MacLellan (19620	69		unknown[c]
Westigard *et al.* (1976)			
1970	76	-	
1971	35	-	
Mean	55		

[a] Data collected from caged studies.
[b] Standard deviation
[c] Based on the percent of hits from total number of hatched eggs.

Table 11. Percentage mortality of *Cydia pomonella* 5th instars after leaving the apples (Ferro *et al.* 1975).

Researcher	Mortality (%)	Mortality attributed to
Ferro et al.		
7/10/73	27.5 (n = 193)	disease or climate?
	22.5 (n = 193)	Parasitoid (*Ascogaster quadridentata*)
8/8/73	14.4 (n = 284)	
	5.3 (n = 284)	disease or climate *A. quadridentata*
Boyce (1943)	32	*A. quadridentata*
Cox (1930)	32 - 41	*A. carpocapsae*
Garlick (1948)	21	*A. quadridentata*
Jaynes & Marucci (1947)	14 - 30	% attack by ants
MacLellan (1960)	94	predators on ground
Nel (1942)		
1939/40	5.3	*A. quadridentata, Pimpla heliophilia* and other species
1940/41	12.2	
1941/42	3.8	

4. CONTROL OF CODLING MOTH

ABSTRACT

Mating disruption of codling moth, *Cydia pomonella* (Linnaeus), was studied in six commercial orchards between 1993 and 1999. Field trials were also undertaken to access the efficacy of a light horticultural mineral oil, and an insecticide programme based on the alternation of insecticides across generation, as control strategies for codling moth. Mating disruption with minimum insecticide intervention proved highly successful at reducing codling moth populations to levels where fruit damage was undetectable in most orchards. The number of codling moth sprays was reduced from 11 to 1 or 2 azinphos-methyl sprays per orchard between 1996/97 and 1999/00. The number of MD treatments was reduced from two applications of 1000 dispensers per hectare to one at 500 to 800 dispenses per hectare. At the reduced dispenser rate, there was an increase in pheromone trap catches. The repellent effect and ovicidal activity of the horticultural mineral oil, Sunspray Ultra-fine, applied as a 1 % emulsion at high volume, was evaluated in an apple orchard that had not been treated for codling moth since its inception. Oil residues were not repellent to ovipositing female moths as there was no difference between the number of eggs laid on treated or untreated branches. However, there was a difference between the mean percentage hatch of eggs laid on treated and untreated branch surfaces. When applied topically to the eggs the oil exhibited significant ovicidal activity, one and six day old eggs being equally susceptible. Mortality of treated eggs varied from 18.8 % to 41.2 %. The rotation of the insecticides, tebufenozide, fenoxycarb and azinphos-methyl, applied to the first, second and third generations respectively, provided acceptable control of high codling moth population levels. Where tebufenozide was applied sequentially in a 9-spray programme a high incidence of shallow damage was recorded.

4.1 INTRODUCTION

The codling moth, *Cydia pomonella* (Linnaeus) (Tortricidae) is a key pest in pome fruit orchards in South Africa. In the warmer areas of South Africa moth activity can extend from August to April, a period of 8 months (Myburgh 1980). The first moth flight commences before blossom and egg laying commences prior to and during the blossom stage, with egg hatch and infestation commencing at petal-fall and continuing through three to four successive flights depending on climatic conditions.

This has resulted in the biotic potential of codling moth in South Africa being one of the highest in the world (Myburgh 1980).

Between 1960 and 1997 growers have relied almost exclusively on an organophosphate programme with azinphos-methyl as the central component. Pyrethroids were increasingly used to control codling moth from the late 1970s to the late 1980s, but their use declined because of the detrimental impact they had on the beneficial organisms in the orchard. During the early 1990s up to 14 azinphos-methyl sprays were applied against this pest. The stage had been reached where conventional pesticides were no longer reliable as an exclusive control strategy against codling moth. This was fueled by the detection of high levels of resistance to azinphos-methyl and pyrethroids in the mid-1990s (Riedl *et al.* 1998). There arose a need to assess alternative management technologies, products and programmes to manage codling moth resistance.

The negative impact that insecticides have on the orchard environment has over the years led to research being directed toward the development and evaluation of more environmentally friendly products and control technologies for codling moth. These include insect growth regulators (IGRs) (Hoying & Riedl 1980; Anderson & Elliot 1982; Elliot & Anderson 1982; Purcell & Granett 1986; Badowskwa-Czubik *et al.* 1991; Riedl & Brunner 1996; Cross 1997), biopesticides (Glen & Clark 1985; Ballard 1987; Jaques *et al.* 1981; Jaques 1991; Vail *et al.* 1991; Brunner 1994), oils (Baxendale & Johnson 1990; Warner 1994,1995; Hilton *et al.* 1995; Riedl *et al.* 1995; Brunner *et al.* 1995), mass trapping (Proverbs *et al.* 1975, MacLellan 1976, Hagley 1978, Madsen & Carty 1979), parasite releases (Hassen *et al.* 1988; Nachtigall & Dickler 1992; Knight 1994; Mills 1995; Mcdougall & Mills 1997), sterile insect release (Proverbs *et al.* 1982; Dyck & Gardiner 1992; Dyck *et al.* 1993; Warner 1993) , mating disruption (MD) (Mani *et al.* 1978; Moffitt 1978; Rothschild 1982; Barnes *et al.* 1992; Carde & Minks 1995; Knight 1995; Gut *et al.* 1995; Gut & Brunner 1994,1998) and more recently, the attract and kill technique (Charmillot *et al.* 1996, 1997). At the time that these products or technologies were developed they were either impractical, less effective or more costly than existing insecticides.

The most effective way to manage insecticide resistance in codling moth is to increase the number of non-chemical methods that the grower can implement. Therefore field studies were undertaken on the effectiveness of MD, a light horticultural summer oil, two non-insecticide methods of control, and

two selected IGRs namely the ecdysone agonist tebufenozide and fenoxycarb, a juvenile hormone mimic.

A long term field study was initiated to investigate the efficacy of and problems associated with the implementation of a pheromone-based management strategy for codling moth in several South African pome fruit orchards. The objective of these trials was to reduce codling moth population levels in orchards where resistance to azinphos-methyl was suspected, reduce the number of organophosphate sprays needed to control codling moth, in particular azinphos-methyl. Various trapping methods were used to monitor the seasonal occurrence of codling moth in orchards treated with MD. By studying individual orchards under MD in detail for a number of years it was hoped to obtain a better understanding of the problems associated with MD in South Africa.

Although the traditional target of oil sprays are scale insects and mites, the efficacy of light summer oil is being increasingly studied for the control of other insects, including codling moth. There are two main reasons for this. No resistance to oils has been reported and data suggest that oils are less harmful to beneficial insects and predatory mites than insecticides. The reason for the lack of resistance is that the pesticidal action of oils is considered to be mainly physical, the oil blocking the spiracles and tracheae of the insect.

Many of the newer insecticides that are more environmentally friendly are not as effective as the organophosphates such as azinphos-methyl. This is in part due to a slower reaction time with respect to larval mortality allowing the larvae sufficient time to do superficial damage before dying . They are also considerably more expensive. Consequently such products are not always favourably received or used by the producer. However, if such products can be shown to provide effective control when used in combination with other more effective insecticides there would be a greater tendency for producers to use them. This aspect was therefore investigated.

4.2 MATERIAL AND METHODS

4.2.1 MATING DISRUPTION

Number and timing of pheromone treatments, rates per hectare, and orchard details are given in Tables 1 and 2.

The mating disruption study was started in 1993 on the farm Oak Valley Estates in the Elgin area and extended to 2000. The orchards were selected because codling moth resistance to azinphos-methyl was suspected. Prior to the mating disruption trial the orchards received from 10 to 11 azinphos-methyl sprays annually. Despite the fortnightly codling moth sprays applied to these orchards, moths were consistently active from September to March/April.

During the first season (1993/94) the area under MD was 14.6 ha, consisting of three adjoining orchards (G61, G4T and G4B) forming a block of 11.5 ha (Fig. 1), and one isolated orchard, W17, of 2.9 ha. The three adjoining orchards were separated from each other by roads and windbreaks. The nearest pome fruit orchards to orchard W17 were approximately 500 m away, separated by pastures and dams. Moth activity in a conventionally managed orchard, G5, parallel to G4B, was also monitored using traps and fruit damage assessments. The size of the orchards varied from 2.9 to 5.2 ha. (Table 2). The MD product used was Isomate-C containing 51.8 % (E,E)-8,10-dodecandien-1-ol (E8,E10-12OH): 29.1 % dodecanol (12OH): 6.0 % tetradecanol (14OH) at 165 mg/dispenser. The dispensers were applied as prescribed by the label, at 1000 dispensers per hectare. The first treatment of Isomate-C was applied before emergence of the overwintering population and the second treatment was applied 76-84 days after the first treatment (Table 1). The producer was requested not to apply any codling moth sprays to the trial blocks unless needed. In each orchard four azinphos-methyl sprays were applied to the 1st generation, and thereafter only according to need as indicated by trap catches and the infestation assessments undertaken at the end of each generation. All other pest management treatments were carried out as normal. Sprays that were applied against other pests, such as African bollworm (*Heliothis armigera)*, banded fruit weevil weevil (*Phlyctinus callosus*) and woolly apple aphid (*Eriosoma lanigerum*) could have an unintended controlling or suppressing effect on codling moth. These sprays have been categorized as indirect sprays (Figs 3 to 8). Insecticides applied specifically for codling moth control are referred to as direct sprays.

During the 1994/95 season two additional orchards, G5 and G70, were included in the study. This increased the trial site under mating disruption from 14.6 to 25.1 ha. A conventionally managed orchard, W45, on another part of the farm was used as the control orchard. An additional 55 ha bordering G61, G4T, G4B and G5 was placed under a combined MD and insecticide programme by Oak Valley Estates (Fig.1). The MD product used was Isomate-C Plus (52.9 % E8,E10-12OH, 29.7 % 12OH, 6.0 % 14OH). The first MD treatment was applied as described for the first season at 1000 dispensers per hectare. However, in G70 the 1000 dispensers were placed at 500 points in the

orchard, i.e. each point having two dispensers. Where a second treatment was applied the interval between the first and second hangings ranged from 120 to 127 days. Insecticide sprays were applied as described for the first season. As in the previous season all other pest management treatments were carried out as normal.

During the third season the spray programme was changed from a pure azinphos-methyl programme to a programme consisting of flufenoxuron applied against the 1st generation, fenoxycarb and chlorpyrifos applied against the 2nd generation and azinphos-methyl against the third generation. Between the third and fifth seasons Isomate-C Plus was the only product used on all the orchards. During those years where a second treatment was applied the interval between the first and second hanging was 105 to 114 days (Table 1). Orchard W17 was placed under a conventional programme in the 1995/96 and 1997/98 seasons respectively, while G4T was removed from the pheromone-based management programme and placed under a conventional programme in 1997/98. In 1998/99 orchard G70 was treated with the 'attract and kill' product Sirene and Isomate- C Plus. The Sirene was applied at the rate of 2 drops/tree and the Isomate-C Plus at 500 dispensers/ha. The Sirene was applied to the bark of the tree in the top third of the tree with. The MD product Rak 3 was applied to orchard W17 in 1998/99 and 1999/20. From the third season sprays were only applied to those orchards where traps recorded more than 2 moths/trap/week or accumulated more than 2 moths/trap in successive weeks. If fruit damage exceeded 0.1 % at harvest sprays were considered for the first generation. Between the third and sixth season a conventionally treated orchard, A6, was used as a control orchard as W45 was also placed under a MD/insecticide programme.

4.2.1.1 Monitoring codling moth populations

The efficacy of MD was evaluated using pheromone, bait and light traps and fruit infestation assessments. Between the second and fifth seasons and during the seventh season post-harvest fruit infestation assessments were also undertaken in the MD orchards.

4.2.1.1.1 Pheromone traps

During the first season approximately each hectare of orchard was monitored using three Pherocon 1C pheromone wing traps. One trap was baited with a Trécé 1-mg lure and hung at head height while the other two traps were each baited with Trécé 10 mg lures deployed at two different heights,

one at head height and the other in the top metre of the tree. Each trap was separated by at least 5 rows in order to eliminate possible competition between the traps. The traps were inspected weekly, at which time all codling moth were recorded and removed from the traps. The lures were replaced at intervals of between three and five weeks. Trap bottoms were replaced at the first sign that the gum was losing its tackiness or the bottoms were losing their shape. In subsequent seasons only one of the two 10 mg baited pheromone traps was used per hectare, positioned in the top metre of the tree.

During the 1994/95 season pheromone lures were changed at fortnightly intervals. The changing of the lures in each orchard was staggered, only half the number of lures in each orchard being replaced weekly. This ensured that during each week of monitoring half the lures were not older than one week. It was hoped that this practice would provide more accurate monitoring information. This practise was discontinued in subsequent years all the lures being changed at fortnightly intervals.

4.2.1.1.2 Bait traps

Bait traps contained a bait consisting of a standard mixture of sugar, terpinyl acetate and water (Barnes and Blomefield 1994). The traps were hung at a density of approximately one trap per hectare. Bait traps in each hectare were separated from the pheromone traps by 5 rows. Bait traps were hung at head height and inspected weekly, when all insects were removed and the number of codling moth counted. Most of the old bait was discarded and the containers topped up with fresh bait. The moths were taken back to the laboratory where they were sexed and dissected to determine whether or not they had mated. Females were recorded as having mated if the bursa copulatrix contained a spermatophore or remnants of a spermatophore.

4.2.1.1.3 Black light traps

Between the 1996/97 to 1998/1999 season black light traps were investigated as a monitoring tool. The traps consisted of a 4 watt ultraviolet fluorescent tube powered by a 12 volt sealed lead acid battery charged using a solar panel. The lights switched on at sunset and remained on for 3 and a half hours. Moths attracted to the light were captured in a funnel and bucket trap beneath the light. Dichlorvos strips were used to kill the moths trapped in the bucket. The strips were changed every two weeks. The traps were inspected weekly, the codling moths removed and taken back to the laboratory where they were sexed and dissected under a binocular microscope to determine their

mated state. Traps were positioned within the tree canopy.

4.2.1.1.4 Fruit infestation assessments

Fruit damage assessments were undertaken at the end of each of the first two moth flights and again before harvest. Between 1993/94 and 1995/96 in each orchard block 100 sample trees were identified as follows:

1. Ten sample rows were selected in each orchard block, rows 1 and 3 on each side of the block, and six rows in the central area of the block (Fig. 2).

2. In each sample row, 10 sample trees were chosen - trees 1 and 3 at each end of the row, as well as six trees at random in the central area of the row.

3. All the data were separated into those from outer and inner areas. The outer areas consisted of all the trees in rows 1 and 3 plus trees 1 and 3 in each of the middle rows. The inner area consisted of the six trees in each of the six rows in the central area (Fig. 1).

Twenty fruit were sampled at random from the top and 20 at random from the middle section of each tree. Each fruit was visually inspected, particularly the calyx and stalk area, without removing the fruit from the tree. Any infested fruit was removed from the tree and taken back to the laboratory and inspected with a microscope to determine whether the damage was due to codling moth. The total number of fruit sampled per orchard block was 4 000.

The total number of trees sampled from the inner and outer sampling areas was 36 and 64 respectively. Using this sampling method it was possible to establish the percentage of trees with infested fruit in the inner and outer areas.

From 1996/97 to 1999/20 the number of sample rows was reduced from 10 to 5. The two outer rows and three rows in the centre of the orchard were selected as the sample rows. The position of the trees in each row and the number of fruit inspected per sample tree remained the same as in previous seasons. The total number of fruit inspected per orchard block was 2000

4.2.1.1.5 Post-harvest fruit infestation assessments

From the 1994/95 season post-harvest fruit infestation assessments were undertaken to determine the level of fruit infestation caused by post-harvest populations. In each orchard five rows were selected and any fruit left hanging in the trees were inspected for codling moth damage. In orchard W17 the main cultivar was Starking , 114 Granny Smith trees serving as pollinators. After the harvest of the Starking apples no further codling moth insecticide treatments were applied to W17. During the 1994/95 season, a post-harvest fruit infestation assessment was undertaken on 7 April. All the fruit on 10 randomly selected Granny Smith trees was harvest and inspected for codling moth damage.

4.2.1.1.6 Statistical analysis

An analysis of variance was used to compare the total number of moths caught in 10 mg traps at the two localities in the tree (head height (low); top metre of the tree (high)) replicated in 14 blocks. The same analysis of variance was also undertaken on total trap counts per month (Table 3). A complete randomized design was performed on infested trees and infested fruit with two positions, inner and outer orchard areas, and six random replications repeated for two seasons (Table 6). A split plot analysis of variance with the two seasons as main plots was performed on the percentage infested trees and infested fruit with position as sub-plot (Table 6). A Shapiro-Wilk test for normality was performed for normality and Student's t-LSD was calculated at the 5 % significant level to compare treatment means (Table 7).

4.2.2 HORTICULTURAL OIL

The trial was undertaken on the Bellvue Experiment Farm, Elgin, South Western Cape. The cultivar used was Golden Delicious and the mineral oil tested was Sunspray Ultra-fine applied as a 1 % emulsion at high volume by means of a hand held spray lance. All moths used in the experiment were obtained from a laboratory colony mass reared at Infruitec on a wheat-germ diet described by Guennelon *et al.* 1981. The trials were undertaken in the field as it was considered that this would give a more accurate indication of the controlling effect of the oil when applied under natural conditions.

4.2.2.1 Behavioural and mortality effects

A 2 x 6 factorial experiment in a complete randomized design with four replicates was undertaken. The main effects were the two treatments (oil and water) and the six days of oviposition on the treated surfaces. The parameters measured were the effect of treatment on eggs laid (repellent activity) and egg hatch. Six branches on each of eight trees were enclosed in nylon netting with a mesh diameter of 2 mm. On 17 January 24 closed branches were randomly selected on the 8 treatment trees, the sleeve cages removed, and sprayed with Sunspray Ultra-fine mineral oil to the point of run-off. The other 24 branches were sprayed with water. The sleeve cages were replaced after spraying. On drying (2 to 3 hours) four, three day old mated female moths were released into 8 sleeve cages, four treated with oil and four treated with water. The moths were removed the following morning and the sleeve cages replaced. Four female moths were released into each bag to ensure that sufficient eggs were laid in an evening. This procedure was repeated with another 8 bags for another 5 consecutive days following the treatment with oil and water. On each occasion a new group of three-day old mated female moths were used. Percentage egg mortality was determined after sufficient time had elapsed for all eggs to have hatched. Any eggs that had not hatched were kept at 22°C ± 3°C and observed until it was evident that the larvae were not going to emerge.

4.2.2.2 Topical toxicity over time

A 2 x 6 factorial experiment in a complete randomized design with four replicates was undertaken. The main effects were the two treatments (oil and water) and six days after oviposition. The parameters measured were the effect of treatment on egg hatch. The two treatments were replicated four times with each treatment being applied on six consecutive days following oviposition. To obtain eggs on the branches, six branches on each of eight trees were enclosed in nylon sleeve cages. Four three-day old mated females were released into each sleeve cage. The following morning the moths were removed from the sleeve cages, the sleeve cages remaining in place. After removing the moths eight branches were chosen at random and the sleeve cages removed. Four of the branches were sprayed with oil and four sprayed with water to the point of run-off. After spraying the sleeve cages were replaced. This procedure was repeated for another five consecutive days until all 48 branches had been treated. Percentage egg mortality was determined after sufficient time had elapsed for all eggs to have hatched. Any eggs that had not hatched were maintained at 22°C ± 3°C and observed until it was evident that the larvae were not going to emerge.

4.2.2.3 Statistical analysis

A 2 × 6 Factorial analysis was performed on the logit transformed incidents (Table 33). Means on logit transformed incidence of hatched and dead eggs for behavioural and mortality effects and topical toxicity over time, are given in Tables 34 and 35.

4.2.3 INSECTICIDE ROTATIONS

4.2.3.1 Study site

The insecticides used, grams pure active ingredients and formulations are given in Table 36. The rotations and dates of application are shown in Table 37. Commercial grade insecticides were used in this study. All the insecticides were applied at the registered dose except Treatment 2 which was applied at double the registered dose for codling moth control.

Trials were undertaken at the Bellvue Experiment Farm, Elgin. The 0.9 ha orchard was planted in 1982 and consisted of predominantly Granny Smith, Golden Delicious and Topred apple cultivars. The planting distance was 3x5 m and the trees were 2-3 m high. Up until 1992 no codling moth or broad spectrum insecticide sprays had been applied to the orchard. From 1992 codling moth insecticide evaluation trials were undertaken in the orchard. It is estimated that between 6 and 14 % of the trees were treated with codling moth insecticides per season, the remainder of the trees receiving no codling moth sprays. This allowed populations to build-up to high levels by the end of the season with the majority of the population not coming into contact with insecticides. This ensured that populations retained a high level of susceptibility to the insecticides tested.

The insecticides were applied at high volume with hand-held spray-lances as full cover-sprays to Golden Delicious apple trees to the point of run-off. All 12 treatments were replicated six times on single tree plots in a randomized complete block design. Each plot was surrounded by unsprayed trees. This reduced spray drift and encouraged a high level of infestation potential throughout the experimental plot. The first spray was applied three days after first egg hatch (27 October 1995) on the Granny Smith cultivar. The first eggs of the season were laid on Granny Smith trees as this cultivar blossoms up to two weeks earlier than the other cultivars in the Bellvue orchard. Consequently very little oviposition took place on the other cultivars between the early blossom and

full-bloom period of the Granny Smith cultivar. Three fruit infestation assessments were undertaken. The first and the second assessments were undertaken after the 1st and 2nd moth flights respectively, and at harvest. For the first two assessments 50 fruit were inspected per replicate but not removed from the tree. For the harvest assessment one to two lug boxes of fruit were removed at random from each tree. One hundred fruit were removed at random from the lug boxes and inspected visually for insect damage. The damaged fruit was inspected microscopically to determine whether the damage was due to codling moth. The number of fruit with shallow and deep codling moth damage, and number of larvae alive, dead or missing was recorded. Because the control had a large number of infested fruit per replicate a random sample of 25 fruit was selected from each replicate and inspected.

4.2.3.2 Statistical analysis

The harvest data was analysed using a one way ANOVA and individual treatments were compared using the Student's t-LSD method (Table 38). An analysis of variance was performed on the logit transformed incidence of shallow and deep damage(Table 39). A Shapiro-Wilk test for nomality was performed and Student's t-LSD was calculated at 5 % significant level to compare treatment means.

4.3 RESULTS

4.3.1 MATING DISRUPTION

4.3.1.1 First season (1993/94)

4.3.1.1.1 Pheromone trap counts

Details of pheromone and bait trap counts, insecticides applied and dates of application are given in Tables 3 - 8 and Figs 3 - 10.

Pheromone traps baited with Trécé 10 mg lures in the high position were the most effective at monitoring the seasonal occurrence of codling moth. Based on total trap counts there was a significant difference in the mean numbers of moths caught in the 10 mg baited traps in the high (37.9) than low (17.8) position in the tree ($P = 0.02$). When total trap counts per month where analyzed there were no differences in trap counts between the high and low position in the months of

September, October and November (Table 3). However, for the other months significantly greater numbers of moths were attracted to the traps in the high position. Very few moths were caught in traps baited with 1 mg lures. A total of 17 moths were caught in 15 traps baited with 1mg lures, of which 9 and 7 moths were caught in orchards G4B and W17 respectively, the orchards with the highest populations. Most of these moths were caught during the 1st generation (9 September to 12 December). In all the MD orchards there was a trend for trap catches to increase after lure replacement. This trend was most noticeable in orchard G4B where five prominent trapping peaks generally coincided with the replacement of the pheromone lures (Fig. 10).

During the first season of MD, trap catches indicated consistent moth activity in all the MD orchards (Figs 3 to 8). High moth activity was recorded in orchards G4B and W17 throughout the season. In G4B the catches from the 10 mg traps placed in the top third of the tree rose above a mean of 2 moths per trap on 10 occasions. The consistently high trap catches in G4B was attributed to male moths emigrating from the sprayed G5 orchard that bordered G4B (Fig. 1). The high trap counts in W17 was attributed to an infestation of 9 % in this orchard the previous season. On 7 occasions the mean trap catch reached or rose above 2 moths per trap. However, in W17 and G4B there was a decrease in the mean number of moths per trap per generation as the season progressed.

In contrast to G4B and W17 trap catches in G61and G4T remained below a mean of 1 moth /trap during the first two generation periods, catches increasing during the 3rd generation period in both orchards (Figs 3 and 4, Table 4). The mean trap catch per season was considerably lower in these two orchards than W17 and G4B. Only on one occasion, 16 February, did trap catches rise above a mean of 2 moths per trap in each orchard. Trap catches in the conventionally treated G5 indicated consistent and high codling moth pressure throughout the season despite 11 azinphos-methyl sprays (Fig 7). The highest trap catches in this orchard were recorded during the 3rd generation period. The consistent trap catches recorded throughout the season, without any indication of a drop in trap catches, suggests that the codling moth populations in this orchard are resistant to azinphos-methyl.

4.3.1.1.2 Bait trap counts

Relatively low numbers of moths were caught in the bait traps compared to the pheromone traps. The bait trap catches in G61, G4T and G4B (Figs 3 to 5) were low during the 1st generation increasing from early January to late March. This is in contrast to orchard W17 where low numbers of moths

were consistently caught in bait traps during the 1st generation period. In G4B there was a greater discrepancy between the 10 mg trap catches and the bait traps. Due to the high numbers of moths in this orchard it was expected that the bait trap counts would be higher. Orchard G61 was the only orchard where the mean number of moths per bait trap was higher than that of the 10 mg traps placed high in the tree. In G61, G4T and W17 the bait traps followed a similar seasonal trend to that of the pheromone traps. In G61 the bait trap counts indicated higher populations than the pheromone traps between 22 December and 2 February. From 16 October 1993 to 24 February 1994, a total of 196 moths were recorded from all the bait traps, of which 113 were males and 83 females (Table 5). A high percentage of mating occurred in all the orchards.

4.3.1.1.3 Fruit infestation

Details of fruit infestation are given in Table 8. Infestation in three of the MD orchards, W17, G61 and G4 Top, varied from 0.18 to 0.35%. By comparison, the conventionally managed orchard (G5) had an infestation of 2.68%. Although there was a slight increase in fruit infestation as the season progressed it remained relatively constant from the 2nd to 3rd generation in three of the four MD orchards. The greatest increase in infestation was observed in orchards G4B and G5. Orchard G4B, which bordered G5, had an infestation of 3.6%, higher than that of the control orchard. Most of the infestation in orchard G4B occurred in the sample rows bordering G5. Although all 1st generation infested fruit was located in the sample rows 1 and 3 furthest from G5, 86.7 % and 92.9 % of the infested fruit of the second generation and harvest assessments were in sample rows 1 and 3 bordering orchard G5 respectively. Overall in row 1 bordering G5, 99.3 % of the infested fruit was recorded. In three of the MD disruption orchards and in G5 infestation was highest in the border rows at harvest.

The number of MD treatments and azinphos-methyl sprays that had to be applied to each orchard is a reflection of the infestation potential in each orchard. The two orchards with the lowest percentage fruit infestation, G61 and G4T, received the least number of sprays, i.e. six, with the sixth spray only being applied to half of G61 and a third of G4T. Orchard W17, considered to be a high pressure situation due to a 9% fruit infestation the previous season, received eight sprays. Orchard G4B received 11 sprays due to consistent trap catches as a result of the movement of mated moths into this orchard from G5. Had the area under MD included G5 it is probable that G4B would have received a similar number of sprays to G4T. There is little doubt that had the azinphos-methyl sprays not been

applied, infestation levels would have been considerably higher. The conventionally managed apple orchard, G5, received 11 sprays.

4.3.1.2 **Second season** (1994/95)

Details of pheromone and bait trap counts and fruit infestation are given in Tables 9 -12 and Figs 3 - 9.

4.3.1.2.1 **Pheromone trap counts**

Pheromone traps in MD orchards again consistently caught moths between October and end-March. The orchard with the highest mean moth catch per trap per season was G4B followed by G5 and G70 (Table 9). The orchards with the lowest mean moth catch per trap per season were W17 followed by G4T and G61. Trap catches were not as "spiked" as the previous season and this can be attributed to the lures not only being changed at fortnightly intervals but, the replacement of the lures being staggered.

Orchard G4B again recorded the most moth activity, a mean of 2 moths being reached or exceeded on seven occasions compared to the 10 occasions during the previous season (Fig 5). There was also a small decrease in the mean moths/trap/season in this orchard compared to the previous season (Table 4). The higher moth activity in G4B compared to the other orchards under MD for the second consecutive year can be ascribed in part to the 3.6 % infestation the previous season. The infestation was attributed to mated females immigrating from the conventionally treated G5 orchard into G4B. It was for this reason that the G5 orchard was placed under MD in the 1994/95 trial. The mean number of moths per trap in G4B remained consistently high despite two pheromone treatments and 11 sprays of azinphos-methyl being applied to this orchards. From the trap catches in G4B, it would appear that there were four moth flight activity periods during the 1994/95 season. Although the flight activity periods were not as clearly defined in G5 and G70 moths were also consistently trapped throughout the season. The total number of moths caught in G5 (159) and G70 (142) were similar.

The three orchards with the lowest mean moth catches per trap per season (Table 9) were also those orchards with a reduced spray programme (Figs 3,4 and 6). In W17 the trap catches indicated a consistent but low moth activity, with only 23 moths being recorded over the seven month monitoring

period. This is a considerable reduction on the 189 moths that were caught the previous season in the 10 mg baited traps placed high in the tree. A mean moth catch of one per trap was reached or exceeded on only two occasions compared to the 12 occasions in the previous season. In G4T the trend in trap catches was similar to the previous season although there was an increase in trap catches in March. In G61 the mean number of moths per trap per season increased from 7.8 (1993/94) to 15.8 (1994/95) despite an extra two and a half sprays being applied. On four occasions a mean of 2 moths per trap was reached or exceeded compared to once during the 1993/94 season (Fig 3). This suggests that there was a decrease in MD during the 2nd generation resulting in an increase in fruit infestation during the 2nd generation. Despite the low population in both G4T and G61 the seasonal flight patterns obtained were similar to that obtained in G4B indicating four generation flights. At relatively low population levels the 10 mg lures were able to indicate moth activity periods and a need for sprays during these periods.

Trap catches in the conventionally treated orchard, W45, during the 1993/94 and 1994/95 seasons indicated consistent and high numbers of codling moth throughout the season despite 11 and 12 sprays being applied respectively. The high codling moth pressure was particularly evident in the 1993/94 season where high numbers of moths were still being caught in April. The mean trap catch for the 1993/94 season (277.3) was considerably higher than that in 1994/95 (186.3) season. During the 1994/95 season moth catches dropped off in mid-January to the end of the season. This decrease in trap catches despite a higher fruit infestation than the previous season can possibly be attributed to the traps having to compete with an exceptionally large number of female moths in the orchard and consequently becoming less effective.

Only eight moths were caught in the 28 traps baited with 1 mg lures over a seven week period (8 November to 28 December). No moths were caught in W17 orchard; one moth in each of G4T, G5 and G61 and two and three moths in G4B and G70 respectively. In orchards with low populations (W17, G4T and G61) and high population (G5) few moths were caught in the 1 mg baited traps, questioning the use of the 1 mg lure in MD orchards. However, the moth catches in these traps indicate that, even at low population levels, CM males are still able to locate the traps and therefore, possibly , calling females.

4.3.1.2.2 Bait trap counts

The bait traps provided a similar seasonal trend to the previous seasons results, low to no counts in

the beginning of the season with an increase in counts toward end-December to April. Except for orchards G4B and G5 the mean number of moths per trap per season was similar for bait and pheromone traps. However, bait traps again tended to catch more moths in the second half of the season than pheromone traps . This was particularly evident in orchards G4T and G70, the bait traps indicating the presence of higher populations than the pheromone traps (Figs 4 and 8) . From 14 September 1994 to 18 March 1995, a total of 466 moths were recorded from all the bait traps, of which 280 were males and 186 females (Table 10). Forty-four percent of the female moths had mated. The lowest percentage of mated females was recorded in W17 (21.4%) and the highest percentage of mated females (50.9 %) was recorded in G70.

4.3.1.2.3 Fruit infestation

Details of fruit infestation are given in Table 6,7 and 11. Infestation in the MD orchards ranged from 0.05 % to 0.53 %. An analysis of the past two seasons fruit infestation data showed no significant difference in the percentage of infested trees and infested fruit in the inner and outer sampling areas during the 1993/94 and 1994/95 seasons respectively (Table 6). However, there were significantly more infested trees in the outer sampling area during the 1993/94 season than during the 1994/95 season (Table 7). No significant differences were obtained when the percentage of fruit infested from each sampling area were compared.

In orchard G4T infestation after the 2nd generation flight was 0.08 % which is the same as the previous season's infestation assessment for the 2nd generation. Although a harvest assessment was not possible as the fruit was harvested by the producer before a fruit assessment could be undertaken, the fruit infestation assessment undertaken by the producer at harvest was 0.5 %. This assessment was based on fruit from the cull bins and bins sent to the packhouse. This orchard received only 4 azinphos-methyl sprays, representing a 62% reduction in the number of sprays applied to this orchard compared to when G4T was under a conventional programme.

Although fruit infestation in W17 was maintained at a similar level to that of the previous season the number of sprays were reduced from 10 to 6. Infestation in W17 increased from 0 % for the first generation to 0,9% for the second generation, decreasing to 0,5% for the third generation. The increase in infestation between the first and second flights is attributed to an increase in mating just prior to the second Isomate-C Plus treatment being applied on 6 January 1995, 122 days after the first

pheromone treatment. The infestation that took place during the 2nd generation moth flight was judged (based on larval instar head capsule measurements) to have taken place just prior to the second application of pheromone dispensers. Although trap catches in W17 were very low, the bait traps indicated the presence of a higher moth activity toward the end of December and first half of January, which coincided with the end of the first pheromone treatment.

The number of sprays in G61 increased from 6 (1993/94) to 8 and fruit infestation decreased from 0.28% (1993/94) to 0.05% (1994/95). An increase in the number of sprays was considered necessary because of an increase in moth activity during the 3rd generation period the previous season, resulting in an increase of 1st generation moths during the 1994/95 season. Despite an increase in the number of sprays and reduced infestation, there was consistent moth activity during the 2nd and 3rd generation periods. This suggests that the sprays of azinphos-methyl were not having the desired effect of reducing populations to levels where MD was more effective.

Infestation in orchard G4B was reduced from the 3,55% (1993/94) to 0,5%. Because of the high infestation recorded the previous season it was considered unwise to reduce the number of sprays applied to this orchard. During the previous season the infestation recorded in G4B was attributed to mated females moving from the sprayed G5 orchard into G4B. By placing G5 also under a mating disruption and insecticide programme the number of mated females immigrating from G5 to G4B was reduced. Most of the infested fruit in G4B (64%) was recorded from the inner area indicating that there was little, if any, movement of mated females from G5 to G4B.

In G5, which was under MD for the first time, infestation decreased from 2.68 % to 0.53 %, representing a five fold reduction in infestation. A full programme of 11 sprays was applied to this orchard. The points trial orchard G70 (1000 dispensers placed at 500 points per hectare) had an infestation of only 0,23 % at harvest after 11 sprays. This orchard was under MD for the first time and the first year was considered a population reduction exercise. Although the percentage infestation was only 0.23 % the percentage of mated females in this orchard was the highest of the orchards under MD, suggesting that the desired level of MD was not being achieved.

By comparison the conventionally managed orchard, W45, had a very high infestation of 34,0 % at harvest despite 11 sprays being applied to this orchard. The previous season W45 had an infestation of 3,6 % at harvest also after 11 sprays had been applied (Fig 9). The high infestation recorded in

W45 was attributed to an increase in codling moth resistance to azinphos-methyl.

The post-harvest fruit infestation assessments in the MD orchards (Table 10) indicated that inadequate orchard sanitation practices can contribute to the spring population in the following season and negatively impacting on MD. The orchard with the highest percentage infestation was W17 (7.8) followed by G70 and G4T. No infestation was recorded in G4B or G5. The high infestation in W17 was due in part to sprays not being applied to Granny Smith trees after the earlier maturing cultivar, Starking, was harvested. The 114 Granny Smith trees that were distributed through the 2.9 ha orchard served as pollinators. To determine the number of live larvae that were present in these trees all the fruit from 10 randomly chosen Granny Smith trees were harvested and inspected for live larvae. Of the 2 574 fruit inspected, 164 fruit were infested with live larvae (6.4 %) . From these infested fruit a total of 201 larvae were removed, an average of 20 larvae per Granny Smith tree. Poor sanitation measures were also implemented when the Starking apples were harvested , i.e. failure to remove all the fruit from the trees when harvesting the Starking apples. This contributed to a build-up of the pest during the post-harvest period. A high proportion of these larvae enter diapause and emerge as moths the following season.

4.3.1.3 Third season (1995/96)

Details of pheromone and bait trap counts and fruit infestation are given in Tables 13 - 16 and Figs 3 - 9.

4.3.1.3.1 Pheromone trap counts

During the 1995/96 season the method of staggering the replacement of the lures was discontinued, the lures in all the traps being replaced at the same time. This resulted in trap catches fluctuating sharply with the replacement of the lures . Had the lures been changed at weekly intervals it is probable that the trap catches would have been consistently much higher. A similar flight activity was observed in all the MD orchards: there was an increase in trap catches during the first generation period compared to the previous season followed by a decrease in trap catches between January and April. The increase in 1st generation activity was particularly evident in orchards G5 and G70 which were only under MD for the second successive season. This increase in moth activity was probably due to the continued use of azinphos-methyl during the 1994/95 season to control codling moth

populations known to be resistant to this product and a warm summer period that favoured codling moth reproduction and development. Based on a general biofix of 25 September for the Elgin area and degree-days the 2nd generation flight commenced on approximately 20 December 1995 and the 3rd generation flight on approximately 3 March 1996. During the 1994/95 season the 1st generation flight commenced on 20 September and the commencement of the second, third and fourth flights on the 29 November 1994, 21 January 1995 and 12 March 1995 respectively. However, there appeared to be a difference between the first half of the season and the second half of the season. Between January and March there was a decline in the trap counts with low numbers of moths being caught between end-December and April. The decline in trap counts is attributed to the change in the spray programme and cooler conditions during the 1995/96 season. The orchard with the highest mean moth catch per trap per season was G70, followed by G5 and G4B, while the orchards with the lowest were again G4T and G61 respectively.

As a guideline it was recommended that an insecticide treatment should only be considered if a catch of 2 moths per trap per week was exceeded or an accumulation of 2 moths was exceeded over consecutive weeks. In G70 this threshold was exceeded repeatedly during the 1st generation period by all six traps (Appendix 1). The consistently high trap counts during this period necessitated 5 sprays being applied. Pheromone trap catches declined sharply after the 1st generation and commencement of the second moth flight (20 December). Between 3 January and 6 February 1996 only two moths were caught. On 14 February two of the six traps exceeded the recommended treatment threshold (Appendix 1, Blocks 1 and 5). Consequently a spray was applied on 17 February, two weeks before the expected harvest date. Between the 2nd and 3rd generation periods there was a threefold decrease in the mean number of moths per trap per generation. This was due to only 8 moths being caught in three of the six traps (Appendix 1) between 3 January and 10 April 1996.

Although G70 received 9 sprays it would appear from the trap catches that two of the insecticide sprays, the second Dursban treatment on 17 January 1996 (for simultaneous control of woolly apple aphid) and the azinphos-methyl spray on 29 January 1996, were unnecessary as codling moth sprays. Furthermore, based on the trap catches in blocks 2 and 3 the azinphos-methyl spray applied on 17 February to these two blocks was also unnecessary.

The high trap catches during the 1st generation period were unexpected in view of the moderate fruit infestation at harvest (0.2%) the previous season. The high moth counts were also affected by poor

post-harvest sanitation methods being applied during the 1994/95 season. Orchard G70 consists of three orchard blocks and the percentage post-harvest fruit infestation for the three blocks ranged from 1.3% to 6.0%, with an overall mean of 3.1% (Table 12). Each block was separated by a road width. Blocks 1 and 2 were roughly square shaped measuring 115 m x 155 m and 115m x 144 m respectively while block 3 was long and narrow with dimensions of 55 m x 144 m. The highest percentage post-harvest fruit infestation was recorded in block 3. It is probable that this part of G70 is too narrow for effective MD and additional methods need to be implemented to reduce the border effect.

A very positive observation that emerged from the 1995/96 MD studies is a decrease in post-harvest fruit infestation (Table 16) compared to the previous season (Table 12). This suggests that there has been a substantial reduction in the codling moth populations during the 1995/96 season. It also highlights the benefits of low codling moth populations. Orchard sanitation practices such as the removal of all fruit from the trees during and after harvest and the collection and removal of fallen fruit from the orchard after harvest, both labour intensive actions occurring at peak labour demanding periods, become less critical actions in helping to reduce codling moth populations through cultural practices.

Trap catches in G5 and G4B followed a very similar pattern to that obtained for G70 . In orchard G5 the recommended trap threshold was exceeded on a number of occasions between 17 October and 3 January (Appendixes 1, Fig 7). Six sprays were applied over this period. Trap catches declined sharply after 3 January, only five moths being recorded in 4 of the 5 traps for the remainder of the season, a period of 14 weeks. Only in block 2 were moths consistently recorded over a six week period between 30 January and 5 March. The consistent presence of moths in this block resulted in four sprays being applied to the whole orchard. However, despite the absence of sporadic and low trap counts in the other four blocks , the four sprays were applied to the whole of G5. In G4B a similar pattern was observed between 27 December and 16 April, 9 moths being caught in four pheromone traps (Appendix 2, Fig. 5). Although the treatment threshold was not exceeded during this period two codling moth sprays were applied. This would suggest that these sprays were more a precautionary decision on the part of the farm management than a need. No post-harvest fruit infestation was recorded in orchards G5 and G4B (Table16).

In orchard G4T there was a substantial decrease in the mean number of moths caught per trap between the 1st, and 3rd generations (Fig 4, Table 13). Between 3 January and 10 April four moths

were caught in the four pheromone traps (Appendix 2). Although two of these moths were caught during the harvest period and could not have influenced the decision to apply sprays, two sprays were applied during February and March.

In orchard G61 more moths were caught during the 2nd generation period (27) than the 3rd generation period (13). Twelve of these moths were caught in one of the three traps used to monitor codling moth. Orchard G61 consists of two blocks of 1.5 ha each, each block separated by an open space of 7 m. The trap that caught the most moths was hung on a perimeter tree bordering the open space between the two blocks. This suggests that male moths were more readily able to find the trap positioned on the perimeter than the other two traps positioned in approximately the centre of each orchard block. This phenomenon is probably due to dilution of the pheromone along the edges of the orchard and the space between the two orchard blocks. The ability of male moths to find the border trap suggests that mating could be taking place in this area of G61. To prevent mating in this area of the orchard it may be necessary to increase the concentration of pheromone along the border by applying additional dispensers to the border row. One spray was applied 15 February after the treatment threshold was exceeded. The tendency for a single trap to catch high numbers of moths was also observed in other orchards, particularly G5 and G70 (Appendix 1 and 2).

Although the number of sprays applied to the MD orchards was still considered too high from a financial aspect, there was overall a considerable reduction in the mean trap catch of 3rd generation moths (Table 13) and percentage fruit infestation (Table 15) compared to the previous season (Tables 9 and 11). This is attributed to the continuation of a combined MD and insecticide programme, a cool spring, and a change from azinphos-methyl to a resistance management spray programme resulting in improved control. The lower 2nd and 3rd generation trap counts indicated that the 1996/97 spring flight would be low with the possibility of omitting or reducing the number of sprays

The trap catches in the conventionally treated orchard that had been under a MD programme during the previous season, W17, remained low throughout the monitoring period. A total of 34 moths were caught in the four traps. Most of these moths were recorded during the 1st generation period (32), only two moths being recorded during the two summer generation periods. Despite the low numbers of moths recorded during the second half of the season a total of 10 sprays were applied. Based on the recommended trap threshold for conventionally treated orchards the five sprays between 3 January

and 12 March were considered unnecessary. The trap catches in the other conventionalyl managed orchard, A6, were very high. There was one pheromone trap in this 2.1 ha orchard. During the monitoring period a total of 496 moths were caught, with most of these moths being recorded during the 1st generation period (365) (Fig 9). Consistently high trap catches necessitated 11 sprays being applied to control codling moth. Despite the 11 sprays being applied and a considerable drop in moth catches during the 3rd generation period, an infestation of 6.3% was recorded prior to harvest (Table 15). This was considerably higher than recorded in any of the MD orchards.

4.3.1.3.2 Bait trap counts

Although bait trap counts were lower than the pheromone traps they provided a similar seasonal pattern to that obtained with the pheromone traps. The bait trap counts tended to be higher earlier in the season than the previous two seasons. The similarity in seasonal occurrence of the pheromone and bait traps, coupled with the low percentage fruit infestation, suggests that the pheromone traps were providing a reliable indication of population trends in MD orchards. However, in the one conventionally treated orchard, W17, 20 moths were recorded between 5 December and 16 March in the bait traps while only two moths were attracted to the pheromone traps. This suggested that there were more moths in the orchard than the pheromone traps were indicating.

A total of 388 moths were recorded from all the bait traps in the MD orchards, of which 233 were males and 155 females (Table 14). Only 18.7 % of the female moths from all the MD orchards had mated, suggesting that there was an increase in the level of mating disruption taking place in the MD orchards. The lowest percentage of mated females was recorded in G70 orchard (5.6 %), the points trial orchard. The highest percentage of mated females (21.7) was recorded in G5 orchard which also had a high level of 1st generation moth activity. Sixty percent of the females caught in W17, the conventionally treated orchard, were mated.

4.3.1.3.3 Fruit infestation

Fruit infestation ranged from 0.3 % to 0 % (Table 15). In three of the six orchards no codling moth damaged fruit was recorded. The low trap catches in the second half of the season and absence of codling moth damaged fruit in three of the five orchards under MD suggested that sprays could possibly be omitted during the 1996/97 season. Infestation in the two conventionally treated orchards,

A6 and W17, was 6.3 % and 0.1 % respectively. The low infestation in W17 was probably due to this orchard being under a MD programme for the previous two seasons.

There was a sharp decrease in the post-harvest fruit infestation compared to the previous two seasons (Tables 12). In only one of the MD orchards was infested fruit recorded (G4T). In W17, 0.3 % infestation was recorded.

4.3.1.4 Fourth season (1996/97)

Details of pheromone, bait and black light trap counts and fruit infestation are given in Tables 17 - 20 and Figs 3 - 9.

4.3.1.4.1 Pheromone trap counts

There was a sharp decline in the trap counts during the 1996/97 season in both the MD and conventionally treated orchards. In all the MD orchards a total of only 22 moths were caught in 22 traps over the monitoring period of 31 weeks, an average of 1.0 moth per trap per season. Only on one occasion was the recommended treatment threshold exceeded, on 2 January 1997 in orchard G5. Most of the moths were recorded in orchard W17 (9), G5 (5) and G61 (5). The first trap catches occurred at the beginning-December with most of the moths being caught during the summer months indicating that despite the almost complete absence of moths during the 1st generation period mating had taken place. In the conventionally treated orchard, A6, a seasonal total of 85 moths were caught compared to the previous seasons total of 496. The slight upswing in trap counts on 18 March is possibly a reflection of the use of azinphos-methyl sprays from 27 January 1997.

4.3.1.4.2 Bait trap counts

Very low numbers of moths were also caught in the bait traps. A total of 24 moths were caught in 22 bait traps. The number of moths trapped in the bait traps was similar to that of the pheromone traps and is a reflection of the low levels to which populations have been reduced in the MD orchards. Most of the moths were caught in orchard G70 (18), between 22 January and 5 March 1997. The number of moths caught in bait traps in orchard G70 was surprising in view of the fact that only 2 moths were caught in pheromone traps in this orchard.

4.3.1.4.3 Black light trap counts

Black light traps (BL) were tested for the first time in the 1996/97 season (Table 18). Light traps were positioned in all MD orchards and the conventionally treated orchard, A6, on 8 January 1997. One light trap was positioned in each MD orchard except in G5 and G70 where two traps were positioned in each orchard. The light traps positioned in W17 and G4B malfunctioned for 12 and 8 weeks, of the 13-week monitoring period, respectively. Most of the moths were caught in G70, an orchard with very low pheromone trap counts. In all the orchards BL traps caught more moths than the pheromone traps. In the MD orchards a total of 147 moths were caught in the 4 BL traps between 8 January and 16 April 1997, compared to the 10 moths caught in 22 pheromone traps over the same time period. Nearly all the moths were caught during February and March. Most of the moths caught in BL traps were male, only 10 females being recorded out of the total catch of 147 moths. None of the female moths had mated. In the conventionally treated orchard, A6, 193 moths were caught in the BL trap compared to 85 moths caught in a pheromone trap baited with a conventional strength monitoring lure. Fifteen females were caught in the BL trap of which 14 had mated.

4.3.1.4.4 Fruit infestation

There was a very sharp decline in the level of fruit infestation in the MD orchards. Fruit infestation ranged from 0.65 % to 0 % (Table 19). In three of the six MD orchards no codling moth damaged fruit was recorded. More damage was recorded during the 2nd generation period than occurred during the previous season. This was surprising in view of the low mean number of moths caught in December. The orchard with the highest fruit damage was W17 that had been conventionally treated the previous season. The increase in infestation is probably due to the reduction in insecticide sprays. The fruit damage in this orchard was unexpectedly high, in view of the previous season's control (0.1 %), and the three Cascade sprays applied to this orchard. In only two orchards was infested fruit recorded during the post-harvest assessments (Fig. 18). Very few codling moth sprays were applied to the MD orchards. In three of the MD orchards no codling moth sprays were applied. Despite a spray not being applied to G5 when the threshold was exceeded no damage was recorded. Only in W17 were three Cascade sprays applied. The low trap catches and absence of codling moth infested fruit at harvest in three of the six orchards under MD suggested that sprays could be omitted during the 1997/98 season.

4.3.1.5. Fifth season (1997/98)

Details of pheromone, bait and black light trap counts and fruit infestation are given in Tables 21 - 24 and Figs 3 - 9.

4.3.1.5.1 Pheromone trap counts

The low trap counts recorded the previous season continued in the 1997/98 season (Table 21). In the MD orchards a total of only 25 moths were caught in 10 traps over a monitoring period of 31 weeks, an average of 2.5 moths per trap per season. However, this average is a bit misleading as most of the moths (19) were recorded in orchard G70. An average of 0.9 moths per season was recorded for the three orchards G4B, G61 and G5 which is similar to last season's average of 1.0. Most of the moths were caught between January and March indicating that although no moths were caught during the 1st generation period and few moths during the 2nd generation period moths were present and mating took place.

In the conventionally treated orchards a total of 4 moths were caught in G4T and 145 moths in W17. Orchard G4T had been under a MD programme for the previous 4 seasons and indicates the extent to which MD has reduced the population level in this orchard. Prior to the MD programme this orchard had received 11 sprays. The four fenvalerate sprays were applied to control the weevil, *Sciobius tottus,* not codling moth. The high trap catches recorded in W17 is surprising in view of the low trap catches the previous season, the low trap catches during the 1st generation period, and the number of sprays applied to this orchard (Fig. 6). This demonstrates the ability of codling moth to increase from what appears to be a well controlled situation. It is possible that the three fenvalerate and two azinphos-methyl sprays, insecticides codling moth is known to be resistant to, did not achieve the desired control. Furthermore, a spray should have been applied on 15 January as the treatment threshold was exceeded. Orchard A6, used as the conventional orchard for the past two seasons was placed under MD by Oak Valley Estates.

4.3.1.5.2 Bait trap counts

In the MD orchards very low numbers of moths were recorded in the bait traps (Table 22). A total of only 14 moths were caught in 20 bait traps, an average of only 0.7 moths per trap per season. The

continued low trap catches in the bait traps is a reflection of the low population levels of codling moth. Most of the moths were caught in orchard G70, the orchard with also the highest pheromone trap catches. In the conventionally treated orchard, W17, 55 moths were caught in 4 bait traps, an average of 13.8 moths per trap per season, which is considerably higher than the MD orchards. The mated status of the females in W17 was very high (95.5 %). In G4T only one moth was recorded which reflects the low codling moth population in this orchard despite no sprays being applied against codling moth.

4.3.1.5.3 Black light trap counts

Although the BL traps again attracted more moths than the pheromone traps there was a decrease in the number of moths caught in BL traps compared to the previous season. A total of 50 moths were caught in 8 BL traps compared to 147 caught the previous season in 4 BL traps. The decrease in the number of moths caught compared to the previous season is attributed to the continuing decline in the population levels the MD orchards. Most of these moths were caught in G70 (29) and G5 (11). Based on harvest and post-harvest fruit assessments lower counts would have been expected in G5. It is possible that the infestation is higher in G5 than is reflected from the fruit assessment at harvest. A high percentage of the moths trapped in all the BL traps were male (90.9 %). In the conventionally managed orchard, W17, that had been in and out of a MD programme, similar numbers of moths were caught in BL and bait traps. In this orchard one of the two BL traps malfunctioned between 12 February and 9 April 1998, the period when most of the moths were recorded. In G4B the two light traps gave repeated problems and were more off than on.

4.3.1.5.4 Fruit infestation

During the 1997/98 season fruit infestation in the MD orchards ranged from 0% to 0.2%, with a mean of 0.05% (Table 23). In 3 of the 4 orchards under MD no codling moth damaged fruit was recorded. Only in G70 was infested fruit recorded. In this orchard the recommended treatment threshold was exceeded on 8 January, 6 and 26 February 1998. The threshold was exceeded on the first two dates by one trap. This trap was situated in G70 but near a pear block that bordered G70. A supplementary spray was applied on 26 February but not for each of the first two dates. A Dursban spray was applied as woolly apple aphid was a problem in the orchard. An infestation of 0.2 % was recorded at harvest. It was initially suspected that this infestation was due to moths emerging from bulk bins

stacked alongside G70. During the post-harvest fruit infestation assessments only in G70 was infested fruit recorded . Although the mean post-harvest infestation for this orchard was 1 % (Table 24) the infestation in the small block (see 1995/96 post-harvest results and Fig. 1.) was 2.1 %. The orchard narrows down considerably at this point where the bins are stacked and it is possible that the border or edge effect is more prominent in this part of the orchard. In W17 the post-harvest infestation was 5.7 %. This was again do to poor post-harvest sanitation methods and the Granny Smith pollinator trees not being sprayed.

The number of insecticide sprays applied to MD orchards ranged from 2 to 4 with a mean of 3 sprays per orchard. However, the insecticide fenvalerate was directed solely at controlling the weevil, *Sciobius tottus*. The weevil was causing extensive damage to the flowers and foliage of the trees.

4.3.1.6 Sixth year (1998/99)

Details of pheromone, bait and BL trap counts and fruit infestation are given in Tables 25 - 28 and Figs 3 - 8.

4.3.1.6.1 Pheromone trap counts

In all the orchards there was an increase in the mean number of moths per trap per season, most of the moths being trapped during March (Table 25). Only in W17 and G70 were moths recorded during the 1st generation period. Orchard Despite G4T being under a conventional spray programme the previous season codling moth trap counts continued to remained low and similar to those of the previous season. In G70 there was a considerable difference between the trap counts inside the orchard and two traps hung on the border row facing an open area where bulk bins were stacked. The traps inside the orchard caught 11 moths while the two traps on the border caught 99 moths between 5 January and 7 April 1999. It was suspected that the bulk bins were responsible for the increase in trap counts in G70. Although the bins were carefully inspected no cocoons or pupal cases could be found. The highest trap counts were recorded in W17 reaching a peak during February/March, despite receiving one pheromone treatment and 5 codling moth sprays.

4.3.1.6.2 Bait trap counts

Bait trap counts were zero to very low in all the orchards except W17 (Table 26). Although the bait trap counts were considerably less than those of the pheromone traps, the seasonal pattern was similar in W17. In W17 90.1 % of the females were mated. suggesting that little if any MD was taking place in this orchard.

4.3.1.6.3 Black light trap counts

Most of the moths were recorded in G70, G5 and W17 (Table 26). In these orchards 216 moths were recorded of which 18.1 % were female in a male to female ratio of 4.5:1. In W17, 75.7 % of the females had mated, of which 5 had mated twice. This is possibly a reflection of the high level of mating that was taking place in this orchard despite one MD treatment and the five codling moth sprays.

4.3.1.6.4 Fruit infestation

Despite an upswing in the trap counts in five of the six orchards surprisingly no codling moth damage was recorded at harvest (Table 27). Although the mean number of moths caught during the 2nd and 3rd generation periods compared to the previous season showed an increase, the increase for the 2nd generation was still relatively low in all orchards except for W17. Furthermore, the fruit in G61 and G70 was harvested toward the end-February before the emergence of moths in March. However, despite the increase in trap counts in orchard G70 the previous season and a pre-harvest fruit infestation of 0.2 %, no infestation was recorded during the 2nd generation period and prior to harvest. Orchard G70 had been treated with Sirene during the first generation period and Isomate-C Plus before the commencement of the 2nd generation. Although a Dursban spray applied to G70 on 27 January would have contributed to codling moth control no sprays during the first generation period had been applied specifically to control codling moth. The data suggests that the Sirene and MD programme appeared to have kept codling moth under control despite the indications of an upswing in the population the previous season. The Dursban spray applied for woolly apple aphid and the azinphos-methyl spray in G5, G4T and G4B would have also contributed to codling moth control. It is possible that the number of fruit sampled at harvest is insufficient to indicate the level of infestation caused by these low population levels. However, low infestation was recorded in five of

the six orchards during the 1st generation period using the same fruit sampling method. Infestation was only recorded in W17. An infestation of 5.2 % was excessive in view of the MD treatment and five codling moth sprays applied to this orchard. This orchard also had a post-harvest fruit infestation of 10.9 % (Table 28).

4.3.1.7 Seventh year (1999/2000)

Details of pheromone and bait traps and fruit infestation are given in Tables 29 - 32 and Figs 3 - 8.

4.3.1.7.1 Pheromone trap counts

In three of the six orchards under MD (G70, G5 and G4B), moths were recorded during the 1st generation period (Table 29). During the 2nd generation period there was also an increase compared to the previous season. The increase in trap counts during the 1st and 2nd generation periods clearly indicated an upswing in the population levels due to inadequate MD being achieved. In W17 there was a sharp increase in the number of moths recorded in pheromone traps, the mean catch per trap per season was 216.8 moths. This figure is similar to counts prior to the introduction of MD.

4.3.1.7.2 Bait trap counts

The seasonal trap counts remained very low in all the orchards except W17, the orchard with the highest pheromone trap counts (Table 30). Excluding W17, the mean catch per trap per season was 0.5. The mean catch per trap per season for W17 was 35. A high percentage of the females in W17 had mated (97.1 %). Most of the matings were single matings, five of the moths mating twice.

4.3.1.7.3 Fruit infestation

Fruit infestation in the MD orchards ranged from 0 % to 32.5 % (Table 31). Despite no codling moth sprays being applied in G61 no fruit damage was recorded. This is probably due the Golden Delicious apples in G61 being harvested toward end-February prior to an upswing in the trap counts on 8 March which was not as prominent in G61. In G70 a higher infestation was expected with a mean trap catch for the 2nd and 3rd generations of 2.8 and 10.2 respectively higher than that recorded in G61. However, the mean trap catch in G70 was misleading as out of a seasonal total of 71 moths

69 were caught in two traps and 57 moths were caught in one trap (trap 5) situated on the border of a small Packham's Triumph pear block attached to G70 (Appendix 3). The other three traps, that monitored the greater part of G70, caught a seasonal total of only two moths. The azinphos-methyl spray applied on 10 February would have also provided a measure of control. The pears were harvested early February and not included in the assessment. In G5 a seasonal total of 68 moths were caught in the pheromone traps. Most of these moths were caught in two traps. Although this total is similar to that of G70 the fruit infestation in the Granny Smith trees prior to harvest was 1.5 %, considerably more than that in G70. The infestation was due to infestation taking place between approximately the 7 and 11 March 2000. The time of infestation was based on the head capsule widths of 24 live larvae removed from apples during the harvest assessment undertaken on 23 March. Of the 24 larvae, 18 were identified as 3rd and 4th instars. Although a flight peak occurred on 8 March 2000, sprays could not be applied because of the danger of exceeding the export residue limits on the Starking apples that where being harvested in G5. Despite a spray being applied on 17 March after the harvest of the Starking apples infestation had taken place in the Granny Smith apples as indicated by the presence of few 1st and 2nd larval instars. Although W17 was under a MD programme it was also under an organic programme with respect to supplementary codling moth sprays. The nine codling moth granulosis sprays applied to this orchard were unable to control codling moth. There was also an increase in the post-harvest fruit infestation in orchards under the combined MD/insecticide programme. The highest post-harvest infestation was also recorded in W17 (Table 32).

4.3.2 HORTICULTURAL OILS

4.3.2.1 Behavioural and mortality effects

Results of the 2 x 6 factorial analysis and details of the mean logit transformed incidence, percentage of hatched and dead eggs and total eggs on treated and control branches on each of the six consecutive oviposition dates following spraying are given in Tables 33 - 35. Based on main effect for treatments there was no significant difference (Table 33) between the number of eggs laid on treated (1821) and control (2061) branches (Table 34). Egg hatch on the treated branches varied from 81.2 % to 92.8 % while egg hatch on the control branches varied from 86.9 to 95.7 % Table 34). There was also no significant difference in the main effect for time (Table 33). This indicates that the oil residue on the branch surfaces did not inhibit oviposition over time when the oil was applied prior

to oviposition.

4.3.2.2 Topical toxicity over time

Results of the factorial analysis and details of the mean logit transformed incidence and percentage of hatched and dead eggs and total number of eggs on the treated and control branches on each of the six consecutive spray dates following oviposition are given in Table 33 - 35. There was a highly significant difference (Table 33) between the main effect for treatments for hatched eggs on treated and control branches, indicating a relationship between egg mortality and oil when applied to eggs topically. The total number of eggs laid on the 24 treated branches was 1145 of which the mean percentage hatch was 68,6 (Table 35). On the control branches a total of 1553 eggs were laid of which the mean percentage egg hatch was 96,7. There was no significant difference in the main effect for time (Table 33) indicating no relationship between egg mortality and the age of the egg when oil is applied to them topically.

4.3.3. INSECTICIDE ROTATIONS

Percentage fruit infestation for the three fruit infestation assessments are given in Table 38 and the details and results of the analysis of variance on shallow and deep fruit damage are given in Tables 40 - 41. The aim of this trial was to determine the overall control achieved with treatments containing combinations of insecticides. However, it was considered that the data of the first two fruit infestation assessments provided information on the level of infestation in each treatment after the first and second flights, particularly for the control treatment.

The first codling moth fruit damage assessment indicated that there was little variation between most of the treatments after the first codling moth generation. An infestation of 13.3% of the fruit on the control trees indicated a relatively high infestation pressure by the 1st codling moth generation. Although an infestation of 5.7% for Treatment 1 may be an early indication that the dosage for this treatment was too low, Treatment 12, which also received three tebufenozide sprays at the same rate (80 ml/100 l water), only had an infestation of 1.0%.

From the fruit damage assessment done on 9 February 1996 an infestation of 48.7% in the control

treatment trees indicated a substantial increase in the population pressure of codling moth for the 2nd generation. Despite the high infestation recorded in the control trees infestation in all the treatments continued to remain low. In view of the high level of infestation recorded in the control trees no treatment showed a marked breakdown in control after two flights of codling moth.

The harvest damage assessment indicated that only Treatments 1,2 and 4 (Control) were significantly different from the other treatments. There were no differences between treatments containing combinations of insecticides (Treatments 6 to 12). The two spray programmes of 9 tebufenozide, applications, even when tebufenozide was applied at double the registered dose (Treatment 2), provided poor control of codling moth (Table 38). The more than 3-fold increase in infestation between the 2nd and harvest assessments for Treatment 1 was not reflected by a similar increase in infestation in the unsprayed control treatment. It is probable that many of the apples on the control trees, infested during the 2nd generation period, fell before the harvest assessment could be undertaken, resulting in a lower infestation than expected. There were also fruit with multiple entry points.

A high incidence of shallow damage was recorded on the fruits of many of the treatments, most of the larvae dying during the 1st larval instar period (Table 40). This indicates death shortly after chewing into the fruit. A high proportion of the larvae in the shallow entry holes could not be found, probably due to many of the larvae disintegrating over time or being dislodged from the shallow hole/depression during spraying or by wind and rain. The incidence of shallow damage was significantly higher at the registered tebufenozide dose of 80 ml/100l water than at the higher rate (Table 41). There was no significant difference between Treatment 1 and Treatment 4 (Control), which understandably also had the highest incidence of deep damage. It would appear that by increasing the dose from 80 to 160 ml/100 l water the time lag between ingestion and mortality was decreased. Although Treatment 3 (9 azinphos-methyl sprays) had the lowest incidence of shallow damage there was no significant difference between this treatment and the recommended resistance management programme,Treatment 9.

Despite the increase in infestation pressure that occurred between the second and third codling moth generations there was not, except for Treatment 1, a large increase in percentage infestation in the various treatments. Treatments 10 and 11, which had three tebufenozide sprays directed against mainly the third generation, were not significantly different from the azinphos-methyl programme

(Treatment 3) or the resistance management programme applied during the 1995/96 season by pome fruit producers (Treatment 9). Where tebufenozide was alternated (Treatment 6) with azinphos-methyl there was no significant difference in the mean infestation compared to the other combinations. (Treatments 3, 5-12). The amount of shallow damage was also similar to the other combinations. It would appear that when tebufenozide is used for the control of only one generation the incidence of shallow damage is limited. However, when it is applied as a full spray programme over the three generations of codling moth there is an accumulative build-up in the incidence of shallow damge.

4.4 DISCUSSION

4.4.1 Mating disruption

4.4.1.1 Reduction of population levels and insecticide sprays

One of the aims of this study was to reduce codling moth population levels in apple orchards where codling moth resistance to azinphos-methyl was suspected and to reduce the number of organophosphate sprays needed to control codling moth, in particular azinphos-methyl. The use of mating disruption proved highly successful at reducing codling moth populations to levels where fruit damage was undetectable in most orchards and minimum spray intervention was necessary. The orchards that had been under a continuous mating disruption programme required only 1 to 2 azinphos-methyl sprays between 1996/97 and 1999/00. This testifies to the outstanding success of a pheromone-based mangement strategy for codling moth control, and highlights the value of MD as the only effective resistance management tool we have available at present.

Between the 1993/94 and 1995/96 seasons population levels remained relatively unchanged despite an intensive control programme of two mating disruption treatments of 1000 dispensers per hectare and 6 to 11 azinphos-methyl sprays. It was only during the 1995/96 season that a sharp decline in codling moth population levels was observed, the decline being confined mainly to the 2nd and 3rd generation periods. However, this decline was also observed in the control orchards A6 and W17, although W17 had also been under a mating disruption programme during the 1993/94 and 1994/95 seasons. The decrease was in part attributed to a change from a spray programme based solely on

the organophosphate, azinphos-methyl, to a resistance management programme, consisting of three sprays of flufenoxuron against the 1st generation, two fenoxycarb and 1 to 2 chlorpyrifos sprays against the 2nd generation and 1 to 4 sprays of azinphos-methyl against the 3rd/4th generations.

It is probable that during the first two years of mating disruption the azinphos-methyl sprays were ineffective against codling moth due to the resistance. The continued use of azinphos-methyl against resistant codling moth populations would probably have further increased the resistance levels, reducing the efficacy of azinphos-methyl. Consequently, population levels under a MD programme would not have declined as rapidly as anticipated. Furthermore, the 1993/94 and 1994/95 seasons were extremely warm and would probably have favoured codling moth reproduction and development. Based on accumulated degree-days the 1993/94 and 1994/95 seasons were the third and second warmest years respectively over a 13 year period (Table 42). It is also probable that the warm conditions would not only have affected the efficacy of azinphos-methyl but also the performance and longevity of the dispensers, particularly during the 1994/95 season. It has been shown that the release rate of pheromone from dispensers increases under air flow versus static conditions (Ogawa 1997) and increases sharply at higher temperatures (Brown *et al.* 1992, Witzgall *et al.* 1999). During the 1993/94 and 1994/95 seasons maximum summer temperatures regularly occurred between 25°C and 30°C (Appendix 5 and 6).

The change to a resistance management programme during the 1995/96 season also coincided with a change in the climatic conditions, the 1995/96 and 1996/97 seasons being considerably cooler than the previous two seasons, particularly during the 1st generation period of the 1996/97 season with a total of only 354 degree-days being accumulated between beginning-September and end-November. Furthermore, between 1 September and 31 December 1996 a total of 356.9 and 528.2 mm of rain was recorded for 1995/96 and 1996/97 seasons respectively. The high rainfall recorded during the spring and early summer period of the 1996/97 season, coupled with lower spring and early summer temperatures, would have resulted in reduced oviposition (Isely 1938) and increased egg and larval mortality (Geier 1963; Hagley 1972; Knight 1998). During the 1996/97 season only individual moths were recorded in pheromone traps in the orchards that had been under four successive seasons of mating disruption.

During the 1998/99 and 1999/00 seasons pheromone trap catches increased toward the end of the season. This increase is attributed mainly to a decrease in the number of mating disruption treatments

and dispensers per season, and three consecutive warm seasons (Appendixes 5-7). Exceptionally low trap counts were recorded during the 1996/97 season. This prompted the decision to reduce the number of mating disruption treatments from two to one in the 1997/98 season in all the mating disruption orchards, except in orchard G5 where two treatments were applied at 800 dispensers per hectare. The continued low trap counts in the 1997/98 season prompted the decision to reduce the number of dispensers. During the 1998/99 season the number of dispensers was halved in all the mating disruption orchards except G5, where 800 dispensers were applied. In the 1999/2000 season the number of Isomate -C Plus dispensers were increased to 800 per hectare because of the increase in moth counts in the second half of the 1998/99 season. However, despite the increase in trap counts during February and March of the 1998/99 season no sprays were applied during the 1st generation period. Fruit damage was recorded in all the orchards except G61.

The findings are similar to those of other researchers. Over a three year study period in South Tyrol, Waldner (1997) reported a reduction in percentage fruit damage and number of sprays in South Tyrol orchards under a pheromone based programme. Prior to the implementation of mating disruption 10 to 40 % fruit damage was recorded despite 3 to 5 insecticide sprays. Fruit damage under a combined mating disruption and insecticide programme varied between 0.3 % and 0.7 %. During the first year of mating disruption the number of codling moth sprays was reduced by two thirds and in the second year of mating disruption the average number of sprays was reduced to 0.6. In those orchards that had been under a mating disruption programme for two years, and where fruit damage was below 1 % without sprays, the number of dispensers was reduced from 1000 to 800/ha. Becid (1997) demonstrated effective control of low population densities of codling moth using only mating disruption, while at high population densities mating disruption was shown to be ineffective on its own.

Gut & Brunner (1998) showed that excellent control of codling moth was achieved in four out of six orchards treated with pheromone. Most of the orchards received only one pheromone treatment. Where populations were low fruit damage was comparable to that recorded in conventional orchards. In orchards with moderate to high population levels mating disruption was unable to provide effective control of codling moth on its own. However, suppression was not improved by increasing the number of pheromone treatments from one to two. In the pheromone treated orchards fruit damage was greater along the borders compared to the interior area. An orchard that showed the greatest border effect was situated adjacent to a block that had an infestation of 15 % the previous season.

Gut & Brunner (1998) considered there to be two reasons for the border effect, i.e. the immigration of mated-females into the pheromone orchard from an infestation source and a lower pheromone concentration on the border than the interior of the orchard leading to more successful communication between the sexes resulting in mating. According to Geier (1981) moths are essentially sedentary, forming discreet populations limited by dispersal barriers such as wind breaks and open ground. There would be a tendency for moths to accumulate on the borders, particularly at the upwind border edge. Witzgall *et al.* (1999) reported significantly lower pheromone concentrations at the upwind edge of the orchard, a constant level of pheromone being reached 10 to 15 m downwind from the orchard border.

In the 1993/94 season the high infestation in G4B occurred along the border adjacent to the conventionally treated orchard G5. The border adjacent to G5 was also the upwind border edge. The high infestation along the border of G4B can probably attributed to the dilution of the pheromone along the border, the immigration of moths from G5 into G4B and the movement of moths inside G4B to the upwind edge of the border. Once G5 had been placed under a mating disruption/insecticide programme in the 1994/95 season the border effect in G4B disappeared. Pheromone from G5 would have been carried downwind into G4B (Witzgall 1999). In Israel, Kehat *et al.* (1995) reported findings similar to those of other mating disruption studies. At low population levels a single pheromone treatment without supplementary sprays provided effective control provided the pheromone treatment is applied before first moth flight. However, where the application of a mating disruption treatment took place after first moth flight one to two sprays were required to control the initial population. However, in general pheromone treatments were supplemented with 1 to 2 insecticide sprays. Area-wide treatment of codling moth with a combination programme of mating disruption and supplementary sprays has resulted in codling moth populations being reduced by 90% within three years (Alway 1998).

4.4.1.2 Timing of MD treatments

It is generally recommended that a pheromone treatment is timed to take place prior to first moth emergence of the spring population. However, in South Africa codling moth has 3 to 4 generations per season with. This means codling moth has to be controlled from approximately mid-October to mid-April. Because of the long control period required, together with high summer temperatures, there is the probability that the pheromone treatment would not result in mating disruption for the full

duration of the control period if the dispensers were applied during late August or early September. The aim of mating disruption was not only to reduce population levels and number of insecticides sprays but also to reduce the need for sprays in the second half of the season. The reason for this is the possibility of incurring fruit damage due to sprays not being applied because of the danger of exceeding the residue limits imposed by the importing country. As population levels drop and pheromone treatments and dispensers are reduced the probability exists that sprays will have to be applied later in the season, particularly under the warm summer conditions occurring in South Africa. Such a situation occurred in G5 during the 1999/00 season. Trap counts indicated the need for an insecticide spray but due to the harvesting period of an earlier ripening cultivar, Golden Delicious, sprays had to be delayed until the harvest of the earlier cultivar was completed. This resulted in a 1.5 % fruit infestation prior to the harvest of the late maturing cultivar, Granny Smith. Many of the these larvae were in the 3rd and 4th instar stage of development and would have emerged from the fruit prior to harvested . These larvae would have entered diapause and emerged the following spring.

During the 1997/98 season the pheromone treatments in orchards G61 and G70 were applied before the flight of the 2nd generation of codling moth. The decision to apply this programme to these two orchards was based on a low mean number of moths per trap per season, no fruit infestation prior to harvest and no post-harvest fruit infestation during the 1996/97 season. Despite no sprays being applied to control codling moth, fruit infestation in G61 remained undetectable, while a low level of infestation (0.2 %) was recorded in G70. This infestation was confined to a narrow area of the orchard which was considered not to be ideal for mating disruption due to a large border effect. During the 1998/99 season the pheromone treatment in G61 was again applied in September. Although the results indicated that at low population levels mating disruption could be achieved by applying the pheromone treatment before the commencement of the second flight the company marketing the pheromone, Biocontrol Ltd, were not in favour of this being recommended.

The spring population arises mainly from 2nd and 3rd generation larvae entering diapause. A mean of 8.7 % of 1st generation larvae enter diapause and contribute to the spring flight (Chapter 4). In South Africa, with its long growing season and warm climate, populations under mating disruption tend to increase toward the end of the season. This suggests that the dispensers may not be releasing sufficient pheromone toward the end of the season to prevent mating from taking place, particularly when the number of dispensers are reduced to 500 to 800/ha for a number of seasons. If the summer generations can be more effectively controlled, fewer larvae will enter diapause to give rise to the

spring flight. Natural mortality during the winter period will further reduce the spring flight. Once codling moth populations have been reduced to undetectable levels at harvest, MD should be aimed at the 2nd and 3rd generations of codling moth, the main contributors to the spring flight. Based on the influence of temperature (Witzgall 1999) and wind (Ogawa 1997) on the release rate of the pheromone from the dispensers, mating disruption will be more effective during the summer months. The spring flight could then be controlled with 1 to 2 sprays timed to co-incide with to peak oviposition or egg-hatch depending on the product being used. This would make it possible to apply pheromone treatments before the emergence of the 2nd flight. If control of codling moth is to be achieved with MD in South Africa it is essential that a higher level of control of the summer generations is achieved.

4.4.1.3 Non-insecticide intervention

Most studies on mating disruption have shown that pheromone based management is not a stand alone approach and will require insecticide intervention from time to time (Riedl *et al.* 1998). During the 1998/99 season orchard G70 was treated with the 'attract and kill' product, Sirene, and mating disruption. This orchard was chosen because of an increase in trap catches during the 1997/98 season indicating the presence of a very low population of codling moth. This would provide an indication of the efficacy of Sirene at low population levels. Furthermore, during the previous season a pheromone treatment had also been applied before the commencement of the 2nd generation flight. The strategy was to treat the 1st generation with Sirene and apply a pheromone treatment to the summer generations.

In most of the apple orchards the first codling moth spray is applied during the blossom period. In the past the application of insecticide sprays during the blossom period, particularly the organophosphate, methyl parathion (Penncap-M), had a negative impact on bees. Where orchards consist of mixed plantings of Granny Smith and Golden Delicious, the Granny Smith trees can blossom up to 2 weeks before Golden Delicious trees. If sprays are delayed until the Golden Delicious have passed full bloom fruit will become infested in the Granny Smith trees. Although 0.1 % fruit damage was recorded during the 1st generation period no fruit damage was detected at the 2nd fruit damage assessment or prior to harvest. In a 4 ha orchard adjoining G70 and under the same codling moth control programme as G70 (three Sirene treatments against the first flight plus a mating disruption treatment prior to the second flight), fruit infestation assessments were also undertaken. No fruit

damage was recorded in this orchard. Although this programme was applied for only one season further studies are required to determine the viability of such a programme over a number of seasons. However, only 2 drops of Sirene were applied to each tree and 500 dispensers per hectare were applied. The summer period was particularly warm and protracted and under such conditions the programme was very successful.

A possible negative aspect of the programme was that 3 treatments of Sirene were needed to control the 1st generation. In areas that have cool climates and 1 to 2 generations per year two treatments of Sirene are sufficient to control low populations of codling moth (Charmillot *et al.* 1996,1997). In the case of large farms the application costs and shortage of labour may discourage many growers from using this strategy, particularly where large trees have to be treated with hand-held applicators. The programme may be applied in hilly areas where it is difficult to achieve proper insecticide coverage with a spray unit or the trees are small and application costs are reduced. A further negative aspect of the attract and kill technique may be the sticky residue that remains on the tree, particularly in the case of three applications per season. This is more noticeable on young trees. However, the success achieved with this programme suggests that it is possible to implement an insecticide free programme for codling moth, should the presence of cross-resistance or resistance develop to one or more of the IGRs the industry is dependant on.

4.4.1.4 Pheromone traps

Monitoring codling moth in mating disruption orchards was based on the use of pheromone traps baited with high release-rate pheromone lures or "superlures" and fruit inspections. The superlures were loaded with 10 mg of Codlemone. The "superlure" is more effective at monitoring codling moth populations in mating disruption orchards than the conventional strength lures used in conventionally treated orchards. These findings are in agreement with those of other researchers (Barrett 1995, Knight 1999). For this reason further use of the standard monitoring lure was discontinued in mating disruption orchards. Although Gut & Brunner (1994) recommended that traps be placed at a mid-height canopy the traps baited with superlures and positioned high in the tree caught in general more moths than traps positioned at head height. This finding is also in agreement with those of Barrett (1995) and Knight (1999). This was in spite of the fact that up to two MD dispensers were also placed high-up in the trees. Barrett (1995) reported that the presence of 3 to 7 dispensers in the tree, did not affect negatively the mean trap catch. However, traps catches are affected when traps are

hung less than a foot from a dispenser (Knight 1999).

The lack of any difference in trap catches between the high and low trap positions in September and October was surprising. It is known that temperature influences the release rate of the pheromone from the dispensers. During cool conditions the release rate is lower than during warm periods (Brown *et al.*1992; Witzgall *et al.* 1999). It is possible that during spring when conditions are cooler and the release rate of the pheromone from the dispensers is lower the moths are able to locate the traps in the low and high positions equally well. The catches in the standard trap may also be a reflection of the cooler conditions in spring.

The increase in trap catches after lure replacement was also observed by other researchers (Gut *et al.* 1995, Knight 1999). Initially the lures were replaced at monthly intervals but after observing the consistent drop in trap catches after the first week of monitoring the lures were changed at fortnightly intervals. However, even by changing the lures at fortnightly intervals a drop in trap catches was observed during the second week. It was hoped to reduce the effect of the fortnightly fluctuations in trap catches and obtain a less erratic seasonal trend by staggering the replacement of the lures in each orchard. After one season this practice was discontinued because it was considered to be too impractical.

Considerable criticism has been levied by local producers, technical advisers and researchers on the reliability of the information generated by pheromone traps baited with the 10 mg lures (Howell & Britt 1994, Gut *et al.* 1995, Varela 1997). Monitoring with pheromone traps is not an exact science, the performance of the trap being influenced by a number of factors under and outside of the control of the producer (Riedl *et al.* 1986). This is particularly so in MD orchards, where the pheromone released from the MD dispensers interferes with the response of the male to the pheromone released from the 10 mg lure in the trap. The problem of monitoring with pheromone traps in MD orchards is magnified as population levels decrease to very low levels. Pheromone trap "shutdown" is not necessarilly a measure of the success of MD, even when traps are baited with 10 mg lures.

The female moth has sedentary behaviour (Geier 1981) and as populations are reduced to low levels the distribution of the pest becomes increasingly patchy, leading to very discrete populations (Geier & Hillman 1971). By only monitoring codling moth adults with pheromone traps such discrete populations may not be detected until sudden increases in moth counts and unexpected damage in

localized areas occur. The formation of discrete populations allows for a greater chance of fortuitous concentrations of the pest and mating (Geier & Hillman 1971). A single mated female in summer can lay a mean of 121 eggs, up to 300 eggs (Chapter 2). The sedentary behaviour of the female results in the eggs being laid in a limited area.

There is also a tendency for the female moth to move within a row rather than between rows (Howell *et al.* 1992). In the absence of sprays, populations can increase very rapidly. In the present study, between the 1997/98 and 1999/00 seasons, there were long periods when no moths were trapped in the pheromone traps. The single trap counts recorded during the 1997/98 season in G4B, G4T, G5 and G61, was probably a reflection of the reduction of populations in the 1996/97 to near discrete populations. It demonstrated the ability of the sexes to communicate and mate at very low population levels, even when the area treated with MD was contiguous. It is possible that the reduction of the MD treatments and dispensers between 1997/98 and 1999/00 increased the dilution effect and allowed a greater degree of mating. This was reflected in an increase in pheromone trap counts, particularly in those traps situated on the borders.

Pheromone traps should be viewed as providing two types of information, historical and immediate. Historical information is that type of information that requires action in the future but not the immediate future. During the 1998/99 season trap counts indicated a build-up of the pest at the end of the season. Despite the increase in trap counts there was no fruit damage except in W17. Although the increase in trap counts was relatively small it must be taken into account that a high proportion of the larvae would have entered diapause to emerge the following spring. The increase in trap counts indicated the need for supplementary 1st generation control measures the following season. When trap counts exceed the recommended treatment threshold a spray is immediately required . It is possible that as populations are reduced to discrete patches, increasing the number of traps from the recommended one per hectare will not increase the accuracy of the trapping information. More information would be generated by increasing the fruit inspections during the season and at harvest.

From the 1997/98 season a treatment threshold of more than two moths per week or during two consecutive weeks was applied (Barnes & Blomefield 1997). This threshold was based on experience and intended as a guideline to producers using MD. However, the threshold was coupled to fruit infestation. If the percentage fruit infestation at the end of the 1st or 2nd generation exceeded 0.1 %, supplementary control measures were considered for the following generation. If fruit infestation at

harvest exceeded 0.05 %, 1st generation sprays were indicated the following season. These recommendations were followed without any major infestation failures. During the 1998/99 season the upswing in trap counts indicated the need for supplementary sprays to the first generation of the 1999/00 season, although fruit infestation was zero in all orchards except W17. The producer did not apply any codling moth sprays due to virtually no trap counts during the 1st generation and low trap counts during the second generation. In all orchards except G61 fruit damage was recorded.

Gut & Brunner (1994) determined that an accumulative catch of between 11 and 15 moths per trap would result in approximately 1 % fruit infestation. These authors considered supplementary sprays necessary if 5 to 7 and 3 to 5 moths are caught for the 1st and 2nd generations respectively. However, supplementary sprays should also be based on visual inspections of 500-1000 fruit in each orchard block after the 1st and about the mid-point of the 2nd generation. In the present trial few traps recorded more than 11 to 15 moths per season where MD was working well. This, in spite of a longer growing season. Howell (1992) considered fruit inspections as the most reliable method for monitoring codling moth. If 10 or more infested fruit were obtained from an inspection of the border trees and two transects through the centre of the orchard supplementary sprays were indicated. The development of such treatment thresholds in MD orchards will always be difficult where the number of treatments and the number of dispensers vary.

In the present study the number of MD treatments, timing of treatments and number of dispensers per hectare varied considerably between 1996/97 and 1999/00 seasons, making it difficult to establish the accuracy of the treatment guidelines recommended by Barnes & Blomefield (1997). The behaviour of the moth may change under different levels of pheromone concentration. Barrett (1995) obtained an increase in the number of moths caught in 10 mg loaded traps when the MD dispensers were increased from 1000 to 2000 per/ha. Furthermore, a change in the loading of the lures or performance of the lures will probably also influence any treatment thresholds. If any change were to be made to the recommendations of Barnes & Blomefield (1997), it would be that consideration should also be given to the number of traps that record moths in the orchard on consecutive monitoring dates. If different traps record moths on consecutive monitoring dates, but the threshold is not exceeded by any one trap it is probably an indication of a low, but general emergence of moths in the orchard. Under such situations a spray is probably required to maintain populations at a level where MD is most effective. An individual trap may exceed the threshold on a number of occasions, as occurred in G70 in the 1999/00 season but the remainder of the traps may not indicate the presence of moths.

Under such circumstances it may not be necessary to spray or to spray the entire orchard before establishing the source and level of infestation. Wherever MD is applied, fruit inspections during the season and at harvest, and experience will play a vital role in the management of codling moth.

4.4.1.5 Black light traps

To augment the information generated by the pheromone traps, black light (BL) traps were introduced into several of the mating disruption orchards. In the first year of using the BL traps (1996) they caught substantially more moths than the pheromone traps, particularly in orchards G61 and G4T, suggesting the presence of higher populations than the pheromone traps were indicating. However, despite the difference between the BL and pheromone trap catches in G61 and G4T, and absence of codling moth sprays, only 0.1 % and 0 % damage was recorded in these two orchards respectively. During the second and third years in which the BL traps were used there was little difference between the BL and pheromone trap catches. This is probably a reflection of lower population levels. The BL traps appeared to be more effective during the 2nd and 3rd generation periods. This is similar to the findings of Sexton (1997). This may be due to pheromone traps being more efficient in spring than summer (Madsen & Vakenti 1972; Howell 1974) and a positive correlation between catch and temperature for BL traps (Howell 1981). Only at higher populations were moths attracted to BL traps during the 1st generation period.

The benefit of BL traps in a mating disruption orchard is that they are not influenced by the pheromone released by the dispensers . They also monitor a larger area (Howell 1983). It is also possible to identify the mated status of the females which provides an indication of level of the mating taking place in MD orchards, and the possible need for supplementary sprays. Howell & Britt (1994) established that a catch of 14 or more female moths indicated the need for supplementary sprays. Howell (1992) considered the number of females caught as unimportant if unmated, suggesting that supplementary sprays are only required once mated females are detected. However, the presence of mated females in MD orchards does not necessarily imply that MD is unsuccessful, as fertility and fecundity may be drastically impaired by delayed mating in MD orchards (Knight 1997).

Contrary to the findings of the other field studies very few females were recorded in BL traps. Both Gehring & Madsen (1963) and Howell (1983) reported a sex ratio (males:females) of 1.2:1, while Howell & Britt (1994) reported an average sex ratio of 1.6:1 from 22 mating disruption orchards.

During the 1996/97 season the sex ratio of male to female caught in BL traps was 11.9:1. The mating status of the females and the number of times females mated can be determined by dissection but this would require a microscope. Once moths enter a light trap they quickly desiccate and becomes hard. Where high numbers of other insects such as bollworm, *Heliothis armigera*, are caught in light traps, scales on the wings of codling moths may get rubbed off making positive identification difficult. Therefore, for reliable identification BL traps need to be inspected at least twice weekly. From a practical perspective it is unlikely that producers would consider this a viable proposition. Other problems encountered with the BL traps were malfunctioning of the light, either as a result of a faulty solar panel or problems with the wiring, and the failure to attract 1st generation moths.

4.4.1.6 Bait traps

Bait traps were also used to augment the information generated from the pheromone trap catches and to determine whether the information obtained could be used to assist in management of codling moth in MD orchards. Although the number of moths caught in the bait traps was generally lower than those in pheromone traps, they provided a similar seasonal trend to that of the pheromone traps in most orchards. As in the case of the pheromone traps there was a sharp decrease in the trap catches between the 1993/94 and 1997/98 seasons, the mean trap catch decreasing from 16.1 moths per trap to 1.1 moths per trap per season. Compared to the pheromone traps the bait traps tended to catch fewer moths during the spring period. These findings were similar to those of Alexander & Carlson (1943).

As in the case of BL traps the sex ratio favoured males but not to the same extent. The average seasonal ratios were 1.4, 1.5, 1.5 and 3.8 males/female for 1993, 1994, 1995 and 1996 respectively. Other studies with fermenting bait traps reported a slightly lower sex ratio of 1.2 males/female (Eyer 1934, Alexander & Carlson 1943), while Nel (1940) reported a sex ratio of 1.4 females/male. As with the light traps the mated status of the females could be determined. This provided an indication of the success of mating disruption and the need for supplementary sprays. There was a gradual decrease in the number of mated females recorded in the bait traps, the percentage decreasing from 59 % to 18.7 % between the 1993/94 and 1995/96 seasons. This was possibly due to MD becoming more effective during the 1995/96 season as population levels decreased.

Bait traps did provide useful information on the mated state of moths and provided, together with

pheromone traps, an indication of population levels. However, it is doubtful whether producers would ever use bait traps to monitor codling moth populations since pheromone traps have been shown to catch more moths and are easier to use and maintain. The producer would have to sex the moths and microscopically determine whether the moths have mated and this would become too time consuming.

4.4.2 Horticultural oil

The similarity between the number of eggs oviposited on treated and control branches indicated that oil residues were not repellent to ovipositing female moths. Riedl *et al.* (1995) found no repellent effect at a concentration of 1 %, but at concentrations of 2 % and 4 % female moths preferred apples without residues when given a choice of treated and untreated apples. There was a higher mortality of eggs laid on surfaces treated with the 1 % oil than on untreated surfaces. This was contrary to the findings of Riedl *et al.* (1995), where mineral oil only showed significant egg mortality at higher concentrations. When applied directly to the eggs the oil exhibited significant ovicidal activity, both one and six day old eggs being equally susceptible, results similar to those of Riedl *et al.* (1995). Egg mortality was low, varying from 18.8 % to 41.2 % with a mean of 31.4 %. This level of mortality was achieved after the branches were thoroughly sprayed to the point of run-off. It is questionable whether sprays applied under South African climatic condition, and in orchards where the trees are large, the desired level of coverage will be achieved to obtain the high level of egg mortality required for export fruit production. Furthermore, most of the sprays are applied at low volume. It is probable that a 2 % rate would provide a higher level of control. However, growers are reluctant to use oils at rates higher than 1 % due to the dangers of phytotoxicity, particularly during hot conditions during and preceding spraying. At a concentration of 1 % the oil can be used to supplement other control technologies such as mating disruption and attract and kill. Brunner *et al.* (1995) obtained very good control in organic orchards when oil sprays at 1 % were combined with mating disruption and Ryania. They found that in single-tree plots four oil sprays were most effective against the 1st generation of codling moth, suppressing fruit damage to levels similar to those obtained with two applications of azinphos-methyl (Guthion 50 WP).

Riedl *et al.* (1995) suggested that maximum toxicity could be achieved by timing the oil sprays in relation to egg-laying activity. Although egg-laying activity is important, the oviposition site can vary through the season and this may also have an impact on the level of toxicity achieved. The danger of phytotoxicity can be reduced by applying the oil during the early part of the season when conditions

are cooler. The early part of the season would also be most ideal because the oviposition behaviour of the moth, and egg and tree development are more favourable for achieving maximum toxicity. The first eggs of the season are oviposited on the wood of the branches and fruit spurs. When the leaves appear, progressively more eggs are laid on the leaves as they grow and develop in size. On those leaves that are still in the process of rapid growth, the eggs appear to be unable to stretch and begin to peel away from the leaf surface. Such eggs are more easily dislodged by rain and wind and are more exposed to dessication. It is possible that a fine layer of oil on the leaf surface may result in eggs not being as firmly attached to the leaf surface. Furthermore, under the cooler weather conditions during the first half of the season, the eggs take longer to develop. At a mean temperature of between 14.8°C and 17.09°C eggs took between 15.5 and 11.6 days to incubate (Chapter 2, Table 2). During this time of the year (September and November) the average temperature is seldom higher than 18°C (Table 43). During this period oils could be applied between 7 and 14-day intervals. If applied at the shorter interval, maximum mortality should be achieved as some eggs would be treated twice or still receive an ovicidal treatment if missed with the previous spray. In contrast, during the summer months it is not only hotter, but more eggs are deposited on areas of the fruit and in areas of the tree that are difficult to reach. This is particularly so for large trees. By mid-summer the trees have become denser, making optimum cover more difficult to achieve (Chapter 1, Conclusion). For these reasons oils would not be considered a good control option in the summer months. Although egg mortality only varied between 18.8 % and 41.2 %, recent field trials with newer horticultural mineral oils applied at high volume during the first flight period indicated that levels in excess of 98 % clean fruit can be expected (T. L. Blomefield, unpublished data).

4.4.3 Insecticide rotations

The aim was to ascertain whether spray programmes consisting of products from different groups of insecticides with different modes of action and levels of efficacy could provide acceptable control of codling moth. Considering that the trial was undertaken in an orchard where the majority of trees were not treated against codling moth, all the combination treatments provided good control of codling moth when compared to an azinphos-methyl programme. The high infestation that occured in the Bellvue orchard should not exist in well managed commercial orchards. Although there are doubts concerning the efficacy of fenoxycarb under South African conditions the 9-spray progamme of fenoxycarb provided equivalent control to that of the 9-spray programme of azinphos-methyl. Valentine *et al.* (1996) in New South Wales, Australia, obtained good control with fenoxycarb and

tebufenozide under high population levels. The resistance management programme (Treatment 9) that was recommended by the industry to producers who suspected resistance and had problems controlling codling moth provided better control of the pest than expected. Similar results were obtained when tebufenozide was used in combination with other products including fenoxycarb. Even when three sprays of tebufenozide were applied at the end of the programme acceptable control was achieved. Under lower infestation levels even better control should be achieved. During a field evaluation trial in a Bon Chretien pear orchard on the Bienne Donne Experiment Farm, Simondium, excellent control (0 % infestation) was achieved with a combination treatment of flufenoxuron/ tebufenozide/azinphos-methyl compared to a control infestation of 18.5 % (T.L.Blomefield, unpublished data).

Fenoxycarb and tebufenozide belong to the juvenile hormone mimic and ecdysone agonist group of insect growth regulators respectively. Fenoxycarb primarily controls the egg stage (Charmillot *et al.* 2001) while tebufenozide is toxic to eggs and young larvae (Pons *et al.* 2000). Pons *et al.*(2000) found that toxicity of tebufenozide varied with the oviposition surface, with very little ovicidal activity when eggs were laid on apples treated in a spray tower. Ovicidal activity was greatest when eggs were laid on a treated surface. However, in a technical information bulletin produced by the manufacturers of tebufenozide, the product is considered to have low ovicidal activity. The high incidence of shallow damage when this product is applied as a full spray programme indicates that ovicidal activity is not high and there is sufficient time between ingestion and cessation of feeding or death, for damage to occur. In the present study by doubling the dose of tebufenozide the amount of shallow damage was significantly reduced compared to the registered dose. Increasing the dose may have reduced the time lag between ingestion and mortality. It is possible that tebufenozide particles, adhering to the mouth parts (mandibles, maxillae and labium) of the larva, enter the oesophagus as the larva crawls over the plant surface. At higher concentrations this inadvertent ingestion may be increased due to more insecticide particles on the plant surface. In the present trial sprays were applied at high volume to the point of run-off resulting in optimum coverage. This is probably the reason for the good performance of the ovicide, fenoxycarb. Under commercial conditions very few sprays are applied at high volume, most sprays being applied at low volume. This may result in poorer results with the IGRs that are predominantly ovicides. When using ovicides optimum cover is essential and many of the sprays are applied under conditions that are not conducive to obtaining good cover (wind, high temperatures).

An important factor is also entry of the larva into the apple. During the inspection of the apples for shallow and deep damage it was noted that a high number of shallow damage marks were recorded on the shoulders of the fruit. The shoulder of the apple is the area where the apples touch or rest against one another and provide the larva with leverage when penetrating the hard waxy skin of the fruit. It is possible that in the case of an insecticide such as tebufenozide increased efficacy may be achieved where apples are thinned to one fruit per spur because larvae weakened by indirect ingestion would not have leverage to damage the fruit. The high number of shallow damage marks and the observation that larval mortality increased with the duration of exposure to treated surfaces (Pons *et al.* 2000), suggested that when products such as fenoxycarb and tebufenozide were used due consideration should be given to oviposition site and surface and entrance of the larvae into the fruit.

During the 1st generation period eggs are laid predominantly on the wood and leaves, while during the summer generations more eggs are laid on the fruit, particularly in the case of the apple cultivar, Granny Smith (Chapter 1). Many of the larvae of the spring generation must therefore crawl a greater distance than larvae of the summer generations, exposing them to the insecticide for a longer period. However, if tebufenozide is primarily toxic by ingestion the site of larval entry into the fruit will be important as more larvae of the 1st generation enter through the calyx (70 %) than the summer generations (30 %)(Chapter 3). It is unlikely that spray material would have penetrated into the calyx area, especially when applied at low volume.

The site of oviposition on the leaf surface also varies according to cultivar and this may also affect the ovicidal performance of the IGRs. Pons *et al.* (2000) treated only the upper surface which is considerably smoother than the lower surface of some apple cultivars . This is particularly so in the case of the Granny Smith and Topred cultivars which have a very dense covering of trichomes (Chapter1). The tricomes form a dense mat that covers the epidermis of the leaf and may affect the amount of insecticide that reaches the leaf surface. In the process of ovipositing the female rubs her ovipositor lobes over the surface. This rubbing action may create an 'opening' in the mat of trichomes and the egg is then laid on the epidermis of the leaf.

The most successful insecticide resistance management strategy is greater use of non-insecticidal control methods. However, many of these methods are more expensive, require greater commitment from the producer in the form of monitoring, management, and knowledge of the biology and behaviour of the pest. There is also greater financial risk should they fail. Consequently the majority

of producers continue to rely in part or solely on insecticides to control codling moth. There is a need to ensure that where insecticide programmes are used, they are applied according to a strategy that delays resistance and prolongs the life of the insecticides presently available to growers. It has been suggested that the most successful resistance managemant strategy, in the absence of cross-resistance, is the alternation of insecticides across generations (Scott 1990; Roush 1993). The rotation trial has shown that a combination of products with different modes of action and levels of efficacy can provide acceptable control of codling moth. Many of the newer products such as fenoxycarb and tebufenozide have a slower reaction time than the organophosphates resulting in superficial damage to the fruit. However, the results clearly indicate that when these products are used in a combination programme excellent control can be achieved, even under high infestation levels and poor thinning practices.

Although good control was achieved with the combination programmes, the difference between the orchard in which the trial was conducted and commercial orchards is the level of susceptibility of the codling moth to the products currently being used against it. In many South African commercial apple and pear orchards, codling moth has developed high levels of resistance to the organophosphate, azinphos-methyl, and the pyrethroids (Addison, pers. comm.). Azinphos-methyl has remained the backbone of the codling moth spray programme from 1959 and pyrethroids were used extensively during the 1980s. A review of the history of codling moth control in South Africa indicated that control strategies based on multiple applications of one insecticide led to increased sprays and suspected resistance to lead arsenate and DDT (Giliomee & Riedl 1998). Welter *et al.* (1992) identified resistance across several insecticide classes in an azinphos-methyl resistant codling moth population from California. This included the IGR fenoxycarb, an insecticide not registered for codling moth control in the United States.

In South Africa laboratory bioassays have identified cross-resistance to diflubenzuron in an azinphos-methyl resistant population (Addison, pers comm.). Even though diflubenzuron was registered for codling moth control few if any producers used this product because it was considered to be ineffective (Blomefield & Swart 1980). Moffitt *et al.* (1988) also detected resistance to diflubenzuron in a codling moth population that had not been exposed to it. Differences in susceptiblity to fenoxycarb and flufenoxuron have also been detected in an azinphos-methyl resistant population in South Africa (Addison, pers. comm.). However, despite these differences no IGR failures have been reported from the field. Resistance studies indicate that it is important to implement control strategies that prevent the pest from evolving an extensive detoxification mechanism against various classes of

insecticides, as has occurred with codling moth in many areas of the world. Once resistance has developed a resistance gene can persist for many years even when the insecticide is withdrawn. Thus the citrus thrips has retained resistance to tartar emetic and DDT for 45 and 35 years respectively (Morse & Brawner 1986). Even though codling moth resistance to azinphos-methyl was lost after six generations (Welter 1992) the presence of resistance alleles in the population persists and prevents the re-use of this insecticide even after full susceptibility has returned (Metcalf 1989).

In the rotational trial sprays were applied at high volume with hand-held spray lances ensuring that optimum cover was achieved even under adverse weather conditions. Under commercial conditions where sprays are applied at low volume it is unlikely that optimum cover will be achieved and the IGR insecticides may not be as effective. Any increase in infestation when using these insecticides will result in producers being less inclined to implement a resistance management programme with these products. Furthermore, the ability to implement an effective resistance management spray programme is limited by the import requirements of the country to which the fruit is being exported. It is also affected by standards imposed by the marketing organizations that buy and distribute the fruit within the importing country. These standards are in many cases set by the communities they serve. This has resulted in producers continuing to use azinphos-methyl and limited use of IGRs.

There is a need for the producer and the fruit industry to realize that pesticide susceptibility is a resource (Phillips *et al.* 1989), and needs to be managed in a manner that is not eroded by poor management practices, i.e. reliance on 1 to 2 products. The exponential rate of increase of insecticide resistance (Metcalf 1989) and the broad base of detoxification abilities that codling moth has evolved, give a clear warning that new insecticides cannot be the solution to resistance. Unless the fruit industry rapidly adopts a control base for codling moth that utilizes an complex of non-insecticide controls it may soon run out of insecticide options and the ability to sustain economic levels of production that permit global competitiveness.

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Table 1. Treatments, rates/hectare and number of applications applied to the mating disruption orchards on Oak Valley Estates, Elgin between the 1993/94 and 1999/20 seasons.

Season	Treatment	No. of dispensers/ha	Dates of pheromone application in orchards					
			G61	G4B	G4T	G70	G5	W17
1993/94	Isomate-C	1000 1000	25 Aug 15 Nov	31 Aug 23 Nov	1 Sept 23 Nov	None	None	31 Aug 15 Nov
1994/95	Isomate-C Plus	1000 1000	1 Sept 5 Jan	7 Sept 6 Jan	2 Sept 5 Jan	1 Sept 5 Jan	7 Sept 6 Jan	5 Sept 6 Jan
1995/96	Isomate-C Plus	1000 1000	9 Sept 22 Dec	14 Sept 27 Dec	14 Sept 27 Dec	7 Sept 20 Dec	14 Sept 28 Dec	None
1996/97	Isomate-C Plus	1000 1000	30 Sept 20 Jan	30 Sept 20 Jan	30 Sept 20 Jan	30 Sept 22 Jan	1 Oct 22 Jan	1Oct 21 Jan
1997/98	Isomate-C Plus	1000 800	1 Dec	8 Sept	None	1 Dec	8 Sept 22 Dec	None
1998/99	Isomate-C Plus	500 800	22 Sept	22 Sept	22 Sept	17 Dec	22 Sept	
	Sirene	2 drops/tree				15 Sept; 16 Oct; 19 Nov**		
	Rak 3	500#						12 Sept
1999/20	Isomate-C Plus	800	15 Sept	15 Sept	15 Sept	15 Sept	16 Sept	
	Rak 3	500						17 Sept

** Sirene was applied to orchard G70 on three occasions during the first generation of codling moth.
# Rak 3 was applied to orchard W17 at 500 dispensers/ha in the 1998/99 and 1999/20 seasons.

Table 2. Description of mating disruption orchards on Oak Valley Estates, Elgin.

Orchards	No. of hectares	No. of trees/ha	Cultivars
G61	3.0	823	Golden Delicious
G4B	4.8	561	Golden Delicious
G4T	3.7	555	Granny Smith
G70	5.3	996	Golden Delicious
G5	5.2	453	Granny Smith
W17	2.9	743	Starking

Table 3. Mean number of *Cydia pomonella* caught in 10 mg pheromone traps at a high and low elevation in the tree with minimum and maximum temperatures for each month.

Month	Mean trap count		Pr > F
	High	Low	
September	0.29	0.43	P = 0.336
October	9.79	6.43	P = 0.302
November	6.36	2.79	P = 0.099
December	5.57	1.93	P = 0.034
January	5.29	1.29	P < 0.01
February	6.43	3.21	P < 0.036
March	4.14	1.14	P < 0.01

Table 4. Mean number of male *Cydia pomonella* caught in 10 mg pheromone traps on Oak Valley Estates, Elgin, during the 1993/94 season.

Orchards	Mean no. of moths caught in:			Mean no. of moths/trap/season
	Sept/Oct/Nov (1^{st} gen.)	Dec/Jan (2^{nd} gen.)	Feb/ Mar/Apr (3^{rd}/4^{th} gen.)	
G61	2.0	1.5	4.3	7.8
G4B	21.5	12.3	10.5	44.3
G4T	1.3	2.3	3.5	7.2
W17	22.1	10.0	8.9	41.0
G5*	63.0	59.0	56.0	177.6

* Monitoring stopped on 1 March

Table 5. Number of male and female *Cydia pomonella* caught in bait traps in MD orchards on Oak Valley Estates, Elgin, during the 1993/94 season.

Orchard	Male	Female	Not mated	Mated	% Mated
G61	18	11	4	7	63.6
G4B	20	16	2	14	87.5
G4T	6	4	0	4	100
W17	69	52	28	24	46.2

Table 6. Analysis of variance of percentage of trees with infested fruit and percentage of infested fruit in the inner and outer sampling areas during the 1993/94 and 1994/95 seasons.

Source	DF	Infested trees (%)		Infested fruit (%)	
		Mean square	Pr >F	Mean square	Pr >F
Season	1	1188.36806	0.0364	3.68890	0.2271
Error (a)	8	1395.64420		3.86287	
Position	1	32.12408	0.6908	1.29157	0.4611
Season*Position	1	730.03472	0.0848	6.78026	0.1140
Error (b)	8	188.82996		2.15524	
Corrected total	19				

Table 7. Percentage trees with infested fruit and percentage infested fruit in the inner and outer sampling areas of the orchards during the 1993/94 and 1994/95 seasons.

Season	Position	n	Infested trees (%)	Infested fruit (%)
1993	Inner	5	29.4 ab	0.9 a
	Outer	5	44.1 a	2.6 a
1994	Inner	5	26.1 ab	1.3 ab
	Outer	5	16.6 b	0.6 a
LSD			20.04	2.14

* Means followed by the same letter(s) do not differ significantly at P = 0.05

Table 8. Percentage fruit infestation by *Cydia pomonella* in MD orchards and a conventionally treated orchard on the Oak Valley Estates, Elgin, during the 1993/94 season.

Orchards	Fruit infestation (%)				
	Codling moth generations				
	1st	2nd	3rd		
			Inner	Outer	Total
Mating disruption					
G61	0	0.25	0.03	0.25	0.28
G4B	0.45	0.75	0.2	3.35	3.55
G4T	0.03	0.08	0.15	0.03	0.18
W17	0.45	0.2	0.13	0.22	0.35
Conventional					
G5	0.43	1.1	0.6	2.08	2.68

Table 9. Mean number of male *Cydia pomonella* caught in 10 mg pheromone traps on Oak Valley Estates, Elgin, during the 1994/95 season .

Orchards	Mean no. of moths caught in:			Mean no. of moths/trap/season
	Sept/Oct/Nov (1^{st} gen.)	Dec/Jan (2^{nd} gen.)	Feb/Mar/Apr ($3^{rd}/4^{th}$ gen.)	
G61	3.3	6.8	5.8	15.8
G4B	8.8	17.5	12.8	39.0
G4T	1.5	2.8	5.5	9.8
G70	8.7	6	9.3	23.7
G5	4.7	14.1	7.7	26.5
W17	1.5	1.8	2.5	5.8
W45	77.0	96.0	13.0	186.3

Table 10. Number of male and female *Cydia pomonella* caught in bait traps in MD orchards on Oak Valley Estates, Elgin, during the 1994/95 season.

Orchards	Male	Female	Not mated	Mated	% Mated
G61	39	12	6	6	50
G4T	25	43	24	19	44.2
G4B	36	21	13	8	38.1
G70	128	55	27	28	50.9
G5	39	41	23	18	43.9
W17	13	14	11	3	21.4

Table 11. Percentage fruit infestation by *Cydia pomonella* in MD and a conventionally treated orchard on Oak Valley Estates, Elgin, during the 1994/95 season.

Orchards	Fruit infestation (%)				
	Codling moth generations				
	1st	2nd	3rd		
			Inner	Outer	Total
Mating disruption					
G61	0	0.03	0.025	0.025	0.05
G4B	0.08	0.43	-	-	-
G4T	0.05	0.08	-	-	-
G70	0	0.05	0.2	0.03	0.23
G5	0	1.48	0.15	0.38	0.53
W17	0	0.93	0.33	0.2	0.53
Conventional					
W45	4.6	17.0	13.5	20.5	34.0

Table 12. Percentage post-harvest fruit infestation by *Cydia pomonella* in MD orchards on Oak Valley Estates, Elgin, during the 1994/95 season.

	Orchards					
	G61	G4B	G4T	G70	G5	W17
Total fruit	479	439	876	1474	288	2574
Infestation (%)	0.2	0	1.8	3.1	0	6.4

Table 13. Mean number of male *Cydia pomonella* caught in pheromone traps in the MD orchards and conventional orchard on Oak Valley Estates, Elgin in the 1995/96 season .

Orchards	Mean no. of moths caught in:			Mean no. of moths/trap/season
	Sept/ Oct/Nov (1^{st} gen.)	Dec/Jan (2^{nd} gen.)	Feb/Mar/Apr (3^{rd}/4^{th} gen.)	
G61	5.7	9.0	4.7	19.3
G4B	10.8	8.0	2.8	21.0
G4T	6.5	1.8	2.3	10.5
G70	21.8	19.3	6.2	47.3
G5	14.8	17.8	3.6	36.2
W17	8.0	0.3	0.3	8.5
A6*	249.0	220.0	27.0	496.0

* One trap used to monitor codling moth

Table 14. Number of male and female *Cydia pomonella* caught in bait traps in the MD orchards and the conventionally treated orchard (W17) on Oak Valley States, Elgin, during the 1995/96 season.

Orchard	Male	Female	Not mated	Mated	% Mated
G61	18	11	10	1	9.1
G4B	33	23	21	4	17.4
G4T	14	15	12	3	20.0
G70	97	36	34	2	5.6
G5	55	60	47	13	21.7
W17	16	10	4	6	60.0

Table 15. Percentage fruit infestation by *Cydia pomonella* in MD and conventionally treated orchards on Oak Valley Estates, Elgin, during the 1995/96 season.

Orchard	Fruit infestation (%)		
	Codling moth generations		
	1st	2nd	3rd
Mating disruption			
G61	0	0	0
G4B	0	0	0.2
G4T	0	0.01	0
G70	0	0	0
G5	0	0	0.3
Conventional			
A6	5.1	2.0	6.3
W17	0.2	0.1	0.1

Table 16. Percentage post-harvest fruit infestation by *Cydia pomonella* in MD orchards on Oak Valley Estates, Elgin, during the 1995/96 season.

	Orchards					
	G61	G4B	G4T	G70	G5	W17
Total fruit	207	723	823	1133	1677	991
Infestation (%)	0	0	0.1	0	0	0.3

Table 17. Mean number of *Cydia pomonella* caught in 10 mg pheromone traps in MD orchards on Oak Valley Estates, Elgin, during the 1996/97 season .

Orchards	Mean no. of moths caught in:			Mean no. of moths/trap/season
	Sept/Oct/Nov (1st gen.)	Dec/Jan (2nd gen)	Feb/Mar/Apr (3rd gen.)	
W17	0.5	1.5	0.3	2.3
G61	0.3	0.3	1.0	1.7
G4B	0.3	0.5	0.5	1.3
G4T	0	0	0	0
G70	0	0.2	0.2	0.3
G5	0.4	1.2	0.3	1.8
W17	0.5	1.5	0.3	2.3
A6 *	23.0	25.0	12.0	60.0

* One trap used to monitor codling moth

Table 18. Number of *Cydia pomonella* moths caught in bait traps in MD orchards and a conventional orchard on Oak Valley Estates, Elgin, during the 1996/97 season.

Orchards	Moths							
Mating disruption	Bait traps				Light traps			
	Male	Female	Not mated	Mated	Male	Female	Not mated	Mated
G61	1	0	0	0	18	1	1	0
G4B	1	0	0	0	-	-	-	-
G4T	0	1	0	1	7	2	2	0
G70	14	4	4	0	90	4	4	0
G5	1	0	0	0	22	3	3	0
W17	1	1	1	0	-	-	-	-
Conventional								
A6	-	-	-	-	178	15	1	14

Table 19. Percentage fruit infestation by *Cydia pomonella* in MD orchards and a conventionally treated orchard on Oak Valley Estates, Elgin, during the 1996/97 season.

Orchard	Fruit infestation (%)		
	Codling moth generations		
	1st	2nd	3rd
Mating disruption			
G61	0.05	0.05	0.1
G4B	0	0.15	0
G4T	0	0	0.05
G70	0	0.05	0
G5	0	0	0
W17	0.2	0.2	0.65
Conventional			
A6	0.8	1.5	0.9

Table 20. Percentage post-harvest fruit infestation by *Cydia pomonella* in MD orchards on Oak Valley Estates, Elgin, during the 1996/97 season.

	Orchards					
	G61	G4B	G4B	G70	G5	W17
Total fruit	377	1152	832	678	537	856
Infestation (%)	0	0	0.7	0	0	0.3

Table 21. Total number of *Cydia pomonella* caught in 10 mg pheromone traps in MD and conventional orchards on Oak Valley Estates, Elgin, during the 1997/98 season .

Orchards	Mean no. of moths caught in:			Mean no. of moths/trap/season
	Sept/Oct/Nov (1^{st} gen.)	Dec/Jan (2^{nd} gen.)	Feb/Mar/Apr (3^{rd} gen.)	
G61	0	0	0.3	0.3
G4B	0	0	1	1
G4T	0	0	2	2
G70	0	3.3	3	6.3
G5	0	0	1	1
W17	2.8	3	61	36.3

Table 22. Number of *Cydia pomonella* caught in bait and black light traps in the MD orchards and the conventionally treated orchards on Oak Valley Estates, Elgin, during the 1997/98 season.

Orchard	Number of moths caught in:							
	Bait traps				Black light traps			
Mating disruption	Male	Female	Not mated	Mated	Male	Female	Not mated	Mated
G61	1	1	1	0	7	0	0	0
G4B	0	1	0	1	3	0	0	0
G70	9	2	1	1	28	1	0	1
G5	0	0	0	0	10	1	1	0
Total	6	3	1	2	48	2	1	1
Conventional								
G4T	0	1	1	0	5	1	1	0
W17*	16	25	1	24	57	8	0	8
Total	20	26	1	21	62	9	1	8

* 14 Moths not sexed or mated state determined

Table 23. Percentage fruit infestation by *Cydia pomonella* in MD and conventionally treated orchards on Oak Valley Estates, Elgin, during the 1997/98 season.

Orchard	Fruit infestation (%)		
	Codling moth generations		
	1st	2nd	3rd
Mating disruption			
G61	0	0	0
G4B	0	0.1	0
G70	0	0.05	0.2
G5	0	0	0
Conventional			
G4 Top	0	0	0
W17	0.1	0.2	0.2

Table 24. Percentage post-harvest fruit infestation by *Cydia pomonella* in MD orchards and conventional treated orchards (G4T, W17) on Oak Valley Estates, Elgin, during the 1997/98 season.

	Orchards					
	G61	G4B	G4T	G70	G5	W17
Total fruit	301	1213	984	968	1312	1921
Infestation (%)	0	0	0	1	0	5.7

Table 25. Total number of *Cydia pomonella* caught in pheromone traps baited with 10 mg lures on Oak Valley Estates, Elgin in the 1998/99 season .

Orchards	Mean no. of moths caught in:			Mean no. of moths/trap/season
	Sept/Oct/Nov (1st gen.)	Dec/Jan (2nd gen.)	Feb/Mar/Apr (3rd gen.)	
G 61	0	0.3	5.7	5
G4B	0	0.3	3.5	3.8
G4T	0	0	1.3	1.3
G70	0.5	0.3	1	1.8
G5	0	1.8	6	8
W17	5.8	22.5	60	88.3

Table 26. Number of *Cydia pomonella* recorded in bait and black light traps in MD orchards on Oak Valley Estates, Elgin, during the 1998/99 season.

Orchard	Bait traps				Black light traps			
	Male	Female	Not mated	Mated	Male	Female	Not mated	Mated
G61	0	0	0	0	3	0	0	0
G4B	0	0	0	0	0	0	0	0
G4T	0	1	0	1	0	1	0	0
G70	4	5	1	4	14	1	1	0
G5	0	0	0	0	14	1	0	1
W17	27	71	7	64	149	37	9	28

Table 27. Percentage fruit infestation by *Cydia pomonella* in MD orchards on Oak Valley Estates, Elgin, during the 1998/99 season.

Orchard	Fruit infestation (%)		
	Codling moth generations		
	1st	2nd	3rd
Mating disruption			
G61	0.1	0	0
G4B	0	0	0
G4T	0.05	0	0
G70	0.1	0	0
G5	0.15	0	0
W17	0.2	3.4	5.2

Table 28. Percentage post-harvest fruit infestation by *Cydia pomonella* in MD orchards on Oak Valley Estates, Elgin, during the 1998/99 season.

	Mating disruption orchards					
	G61	G4B	G4T	G70	G5	W17
Total fruit	451	496	744	417	532	1546
Infestation (%)	0	0.8	0	0	0.2	10.9

Table 29. Total number of *Cydia pomonella* caught in pheromone traps baited with 10 mg lures on Oak Valley Estates, Elgin in the 1999/00 season .

Orchards	Mean no. of moths caught in:			Mean no. of moths/trap/season
	Sep/Oct/ Nov (1^{st} gen)	Dec/Jan (2^{nd} gen)	Feb/Mar/Apr ($3^{rd}/4^{th}$ gen)	
W17	65.3	122.3	29.3	216.8
G61	0	0.7	2.3	2.7
G4B	0.3	0	2.0	2.3
G4T	0	0.3	0.8	1.0
G70	3.6	4.4	6.4	14.4
G5	0.6	2.8	10.2	13.2

Table 30. Number of *Cydia pomonella* caught in bait traps in MD orchards on Oak Valley Estates, Elgin, during the 1999/00 season.

Orchard	Male	Female	Not mated	Mated
G61	0	1	0	1
G4T	0	1	1	0
G4B	2	0	0	0
G70	4	3	0	3
G5	1	0	0	0
W17	31	105	3	102

Table 31. Percentage fruit infestation by *Cydia pomonella* in MD orchards on Oak Valley Estates, Elgin, during the 1999/00 season.

Orchard	Fruit infestation (%)		
	Codling moth generations		
	1st	2nd	3rd
G61	0	0	0
G4T	0	0	0.3
G4B	0	0	0.3
G70	0	0	0.2
G5	0	0	1.5
W17	2.1	10.6	32.5

Table 32. Percentage post-harvest fruit infestation by *Cydia pomonella* in MD orchards on Oak Valley Estates, Elgin, during the 1999/20 season.

	Orchards					
	G61	G4T	G4B	W17	G70	G5
Total fruit	158	344	995	1052	338	518
Infestation (%)	0	0	0	11.4	0.3	0.2

Table 33. Results of the factorial analysis of variance on the logit transformed incidence of number of eggs laid and egg hatch of *Cydia pomonella* eggs over time when treated with Sunspray oil before and after oviposition.

Source	DF	Behavioural and mortality effects (before oviposition)		Topical toxicity over time (after oviposition)	
		Mean square	Pr > F	Mean square	Pr > F
Treatment	1	4.5113	0.0649	66.5311	< 0.001
Time	5	0.5945	0.7902	0.7268	0.8269
Treatment x Time	5	1.4979	0.3269	1.8347	0.3891
Error	36	1.2438		1.7025	
Total corrected	47				
Shapiro-Wilk's test for Non-Normality		P = 0.43		P = 0.14	

Table 34. Means on logit transformed incidence of hatched and dead *Cydia pomonella* eggs recorded on treated and control branches on 6 consecutive oviposition dates following spraying (mean % ( ) and counts [ ] in parentheses).

Treatment dates	Treated branches		Control branches		Main effect for time	
	Eggs		Eggs			
	Hatched	Dead	Hatched	Dead	Hatch	Dead
17/01/94	2.6476 (89.6) [317]	- 2.6476 (10.4) [19]	2.5011 (91.6) [241]	- 2.5011 (8.4) [24]	2.5744 (90.6) [558]	- 2.5744 (9.4) [43]
18/01/94	2.0118 (87.1) [242]	- 2.0118 (12.9) [49]	3.3165 (95.2) [385]	- 3.3165 (4.8) [15]	2.6642 (91.1) [627]	- 2.6642 (8.9) [64]
19/01/94	2.0478 (85.7) [413]	- 2.0478 (14.3) [65]	3.2991 (95.7) [340]	- 3.2991 (4.3) [14]	2.6735 (90.7) [753]	- 2.6735 (9.3) [79]
20/01/94	1.7908 (84.3) [372]	- 1.7908 (15.7) [49]	3.4150 (95.3) [368]	- 3.4150 (4.7) [18]	2.6029 (89.8) [740]	- 2.6029 (10.2) [67]
21/01/94	2.0121 (81.2) [138]	- 2.0121 (18.9) [30]	1.9050 (86.8) [319]	- 1.9050 (13.2) [52]	1.9585 (84.0) [457]	- 1.9585 (16.0) [82]
22/01/94	2.5381 (92.8) [339]	- 2.5381 (7.1) [25]	2.2904 (86.9) [408]	- 2.2904 (13.1) [70]	2.4142 (89.9) [747]	- 2.4142 (10.1) [95]
Main effect for treatments	2.1747 (86.8) [1821]	- 2.1747 (13.2) [237]	2.7878 (91.9) [2061]	- 2.7878 (8.1) [193]		

Table 35. Means on logit transformed incidence of hatched and dead *Cydia pomonella* eggs recorded on treated and control branches on 6 consecutive spray dates following oviposition (mean % ( ) and counts [ ] in parentheses).

Treatment dates	Treated branches		Control branches		Main effect for time	
	Eggs		Eggs			
	Hatched	Dead	Hatched	Dead	Hatched	Dead
18/01/94	0.9063 (67.6) [245]	- 0.9063 (32.4) [96]	3.9312 (98.4) [274]	- 3.9312 (1.6) [4]	2.4187 (83.0) [519]	- 2.4187 (17.0) [100]
19/01/94	1.9062 (83.8) [227]	- 1.9062 (16.2) [38]	3.3412 (96.9) [269]	- 3.3412 (3.1) [8]	2.6237 (90.4) [496]	- 2.6237 (9.6) [46]
20/01/94	1.9138 (80.9) [202]	- 1.9138 (19.1) [53]	2.7734 (94.6) [258]	- 2.7734 (5.4) [14]	2.3436 (87.7) [460]	- 2.3436 (12.3) [67]
21/01/94	0.3690 (59.2) [173]	- 0.3690 (40.8) [107]	3.3374 (97.0) [275]	- 3.3374 (3.0) [8]	1.8531 (78.1) [408]	- 1.8531 (21.9) [115]
22/01/94	0.4122 (59.4) [168]	- 0.4122 (40.6) [157]	3.4752 (96.7) [198]	- 3.4752 (3.3) [8]	1.9437 (78.0) [366]	- 1.9437 (22.0) [165]
23/01/94	0.6684 (61.0) [170]	- 0.6684 (39.0) [107]	3.4452 (96.6) [279]	- 3.4452 (3.4) [10]	2.0568 (78.8) [619]	- 2.0568 (21.2) [117]
Main effect for treatments	1.0293 (68.6) [1145]	- 1.0293 (31.4) [558]	3.3839 (96.7) [1553]	- 3.3839 (3.3) [52]		

Table 36. Grams pure active ingredient, dosage and formulation of each insecticides used in the rotational field evaluation trial.

Insecticides	Grams pure a.i.	Dosage (per 100 l water)	Formulation
Tebufenozide	240 g/l	80 ml	SC
Tebufenozide	240 g/l	160 ml	SC
Flufenoxuron	100 g/l	25 ml	DC
Azinphos-methyl	350 g/kg	50 g	WP
Fenoxycarb	250 g/kg	30 g	WP

Table 37. Rotation treatment regimes used and dates of spray applications.

Treatment	Spray date								
	1995					1996			
	30 Oct	13 Nov	27 Nov	11 Dec	26 Dec	9 Jan	22 Jan	5 Feb	19 Feb
1	Te80	Te80	Te80	Te80	Te80	Te80	Te80	Te80	Te80
2	Te160	Te160	Te160	Te160	Te160	Te160	Te160	Te160	Te160
3	Am	Am	Am	Am	Am	Am	Am	Am	Am
4	Untreated control								
5	Fen	Fen	Fen	Fen	Fen	Fen	Fen	Fen	Fen
6	Am	Te80	Am	Te80	Am	Te80	Am	Te80	Am
7	Am	Am	Am	Te80	Te80	Te80	Am	Am	Am
8	Flu	Flu	Flu	Te80	Te80	Te80	Am	Am	Am
9	Flu	Flu	Flu	Fen	Fen	Fen	Am	Am	Am
10	Flu	Flu	Flu	Am	Am	Am	Te80	Te80	Te80
11	Flu	Flu	Flu	Fen	Fen	Fen	Te80	Te80	Te80
12	Te80	Te80	Te80	Am	Am	Am	Te80	Am	Am

* Abbreviations used: Te80 - Tebufenozide 80 ml/100 l water
Te160 - Tebufenozide 160 ml/100 l water
Am - Azinphos-methyl
Fen - Fenoxycarb
Flu - Flufenoxuron

Table 38. Total number of fruit infested by *Cydia pomonella* and mean infestation (%) for the twelve treatments on , 11 December 1995, 9 February and 9 March 1996.

Treatment	11 December 1995		9 February 1996		9 March 1996	
	Total infested fruit	Mean infestation (%)	Total infested fruit	Mean infestation (%)	Total infested fruit	Mean infestation (%)
1	17	5.7	19	6.3	114	19.1c*
2	3	1	16	5.3	56	9.5 b
3	1	0.3	12	2.3	7	2.3 a
4	40	13.3	146	48.7	317	53.1d
5	6	2	6	2	30	5.0 ab
6	1	0.3	4	1.3	24	4.1 a
7	2	0.7	7	2.3	36	6.0 ab
8	3	1	2	0.7	31	5.2 ab
9	7	2.3	4	1.3	11	1.8 a
10	3	1.1	6	2	18	3.6 a
11	2	0.7	6	2	21	3.5 a
12	3	1	9	3	16	2.5 a

* Means followed by the same letter(s) do not differ significantly at P = 0.05

LSD (P = 0.05) = 5.19

Table 39. Results of the analysis of variance on the logit transformed incidence of shallow and deep damage by *Cydia pomonella* larvae on apples treated with different insecticide programmes.

Source	DF	Shallow		Deep	
		Mean square	Pr > F	Mean square	Pr > F
Blocks	5	0.7825	0.298	0.85854	0.169
Treatments	11	4.1763	< 0.001	8.7089	< 0.001
Error	55	0.6257		0.5286	
Total corrected	71				
Shapiro-Wilk's test for Non-Normality		P = 0.0633		P = 0.3998	

Table 40. Number of fruit with shallow or deep *Cydia pomonella* damage in the twelve treatments.. Larvae were recorded as alive, dead, emerged with the composition of the number of instars of alive (A) and dead (D) larvae found in the fruit.

Treatments	Shallow	Deep	Missing	Emerged	Larvae		Larval instars									
					Alive	Dead	1		2		3		4		5	
							A	D	A	D	A	D	A	D	A	D
1	104	19	53	6	5	59	53	1	2	1	4	1	0	1	0	1
2	52	9	17	3	4	37	34	0	1	0	1	0	1	1	0	1
3	5	2	1	0	1	5	0	3	0	1	1	1	0	0	0	0
4	69	125	87	40	45	22	6	1	7	9	5	13	2	14	2	8
5	21	12	23	2	4	4	0	3	0	1	3	0	1	0	0	0
6	22	5	13	1	1	12	0	10	0	1	1	1	0	0	0	0
7	32	5	12	1	1	23	0	22	0	1	1	0	0	0	0	0
8	34	3	18	0	3	16	0	12	1	4	2	0	0	0	0	0
9	15	1	7	0	0	9	0	7	0	1	0	1	0	0	0	0
10	32	6	17	0	3	18	0	16	2	1	0	0	0	1	1	0
11	23	0	16	0	0	7	0	5	0	1	0	1	0	0	0	0
12	16	0	8	0	0	8	0	7	0	0	0	1	0	0	0	0

Table 41. Total number of shallow and deep fruit damage by *Cydia pomonella* larvae for each treatment with the logit transformed means (original mean percent fruit infestation in parenthesis).

Treatments	Total shallow damage	Logit transformed means (%)	Total deep damage	Logit transformed means (%)
1	104	-1.6566 a (17.4)	19	-3.4697 b (3.7)
2	52	-2.5992 bc (8.8)	9	-4.2386 bcd (1.5)
3	5	-4.5686 e (0.8)	2	-4.9270 de (0.3)
4	69	-1.6988 ab (15.9)	125	-0.8838 a (29.4)
5	21	-3.4537 cd (3.8)	12	-4.0089 bc (2.0)
6	22	-3.5493 d (3.7)	5	-4.5993 cde (0.8)
7	32	-2.9372 cd (5.3)	5	-4.7023 cde (0.8)
8	34	-2.9017 cd (5.7)	3	-4.6955 cde (0.5)
9	15	-3.7937 de (2.5)	1	-5.1185 e (0.2)
10	32	-3.4212 cd (2.5)	6	-4.4936 cde (1.1)
11	23	-3.3129 cd (3.8)	0	-5.3033 e (0.0)
12	16	-3.5291 d (2.7)	0	-5.3033 e (0.0)

* Means followed by the same letter(s) do not differ significantly at P = 0.05

LSD (P = 0.05) for shallow damage = 0.9152

LSD (p = 0.05) for deep damage = 0.8413

Table 42. Accumulative degree-days for the 1st, 2nd and 3rdgeneration periods of *Cydia pomonella* from 1987/88 to 1999/00. Accumulative degree-days (10·C) based on hourly temperature data from the Elgin Experiment Farm, Elgin.

Year	Accumulative degree-days for:			Total
	Sept - Nov (1st gen)	Dec - Jan (2nd gen)	Feb - Mar (3rd gen)	
1987/88	439	512	580	1531
1988/89	434	580	503	1517
1989/90	400	546	509	1455
1990/91	404	506	493	1403
1991/92	412	530	536	1478
1992/93	452	573	571	1596
1993/94	538	632	579	1749
1994/95	600	598	590	1788
1995/96	452	607	513	1572
1996/97	354	546	516	1416
1997/98	568	540	585	1693
1998/99	444	612	603	1659
1999/00	570	728	711	2009

Table 43. Average monthly temperatures on the Elgin Experiment Farm, Elgin for the months of September to December between 1993 and 1999.

Year	September	October	November	December
1993	13.8	15.8	17.9	18.7
1994	13.7	16	16.5	18.7
1995	13.5	13.7	17	19.2
1996	12.1	14.2	14.4	18.1
1997	15.5	19.4	17	19.3
1998	12.7	15.5	16.3	19.7
1999	18.8	16.2	17.5	21.8

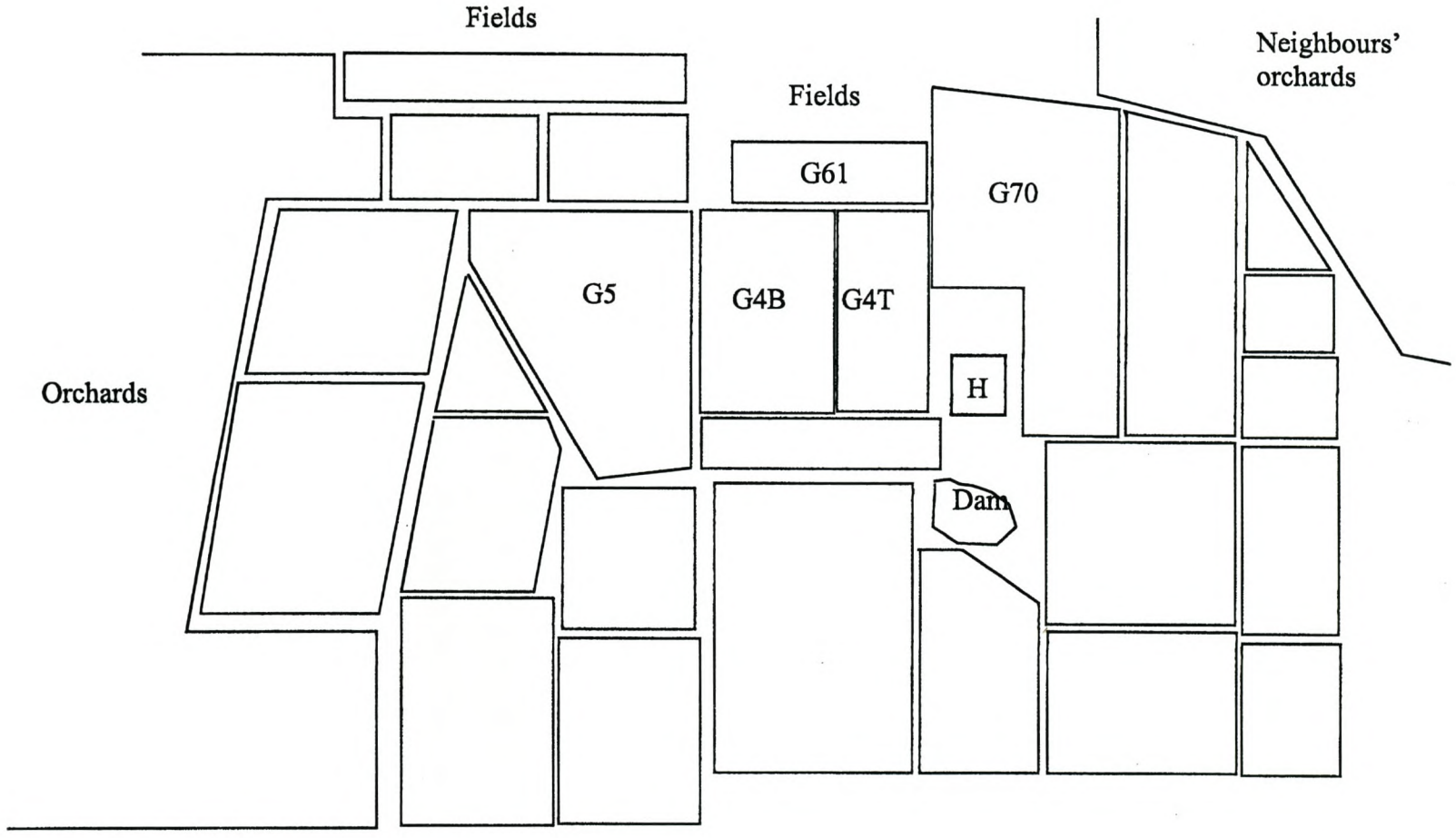

Fig. 1. Map of the position of the mating disruption trial orchards and bordering orchards on Oak Valley Estates, Elgin.

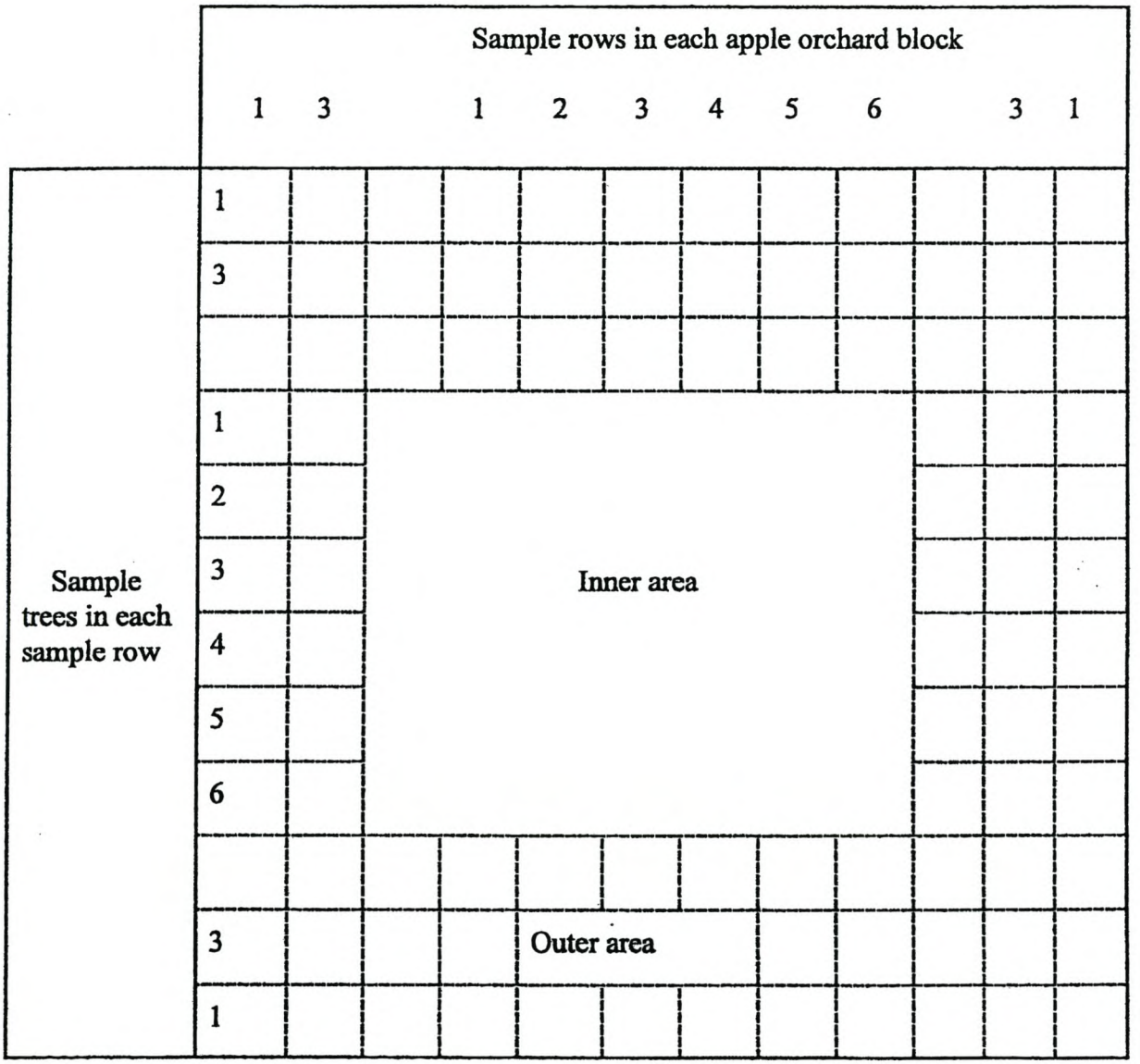

Fig. 2. Orchard plan of sample rows and trees

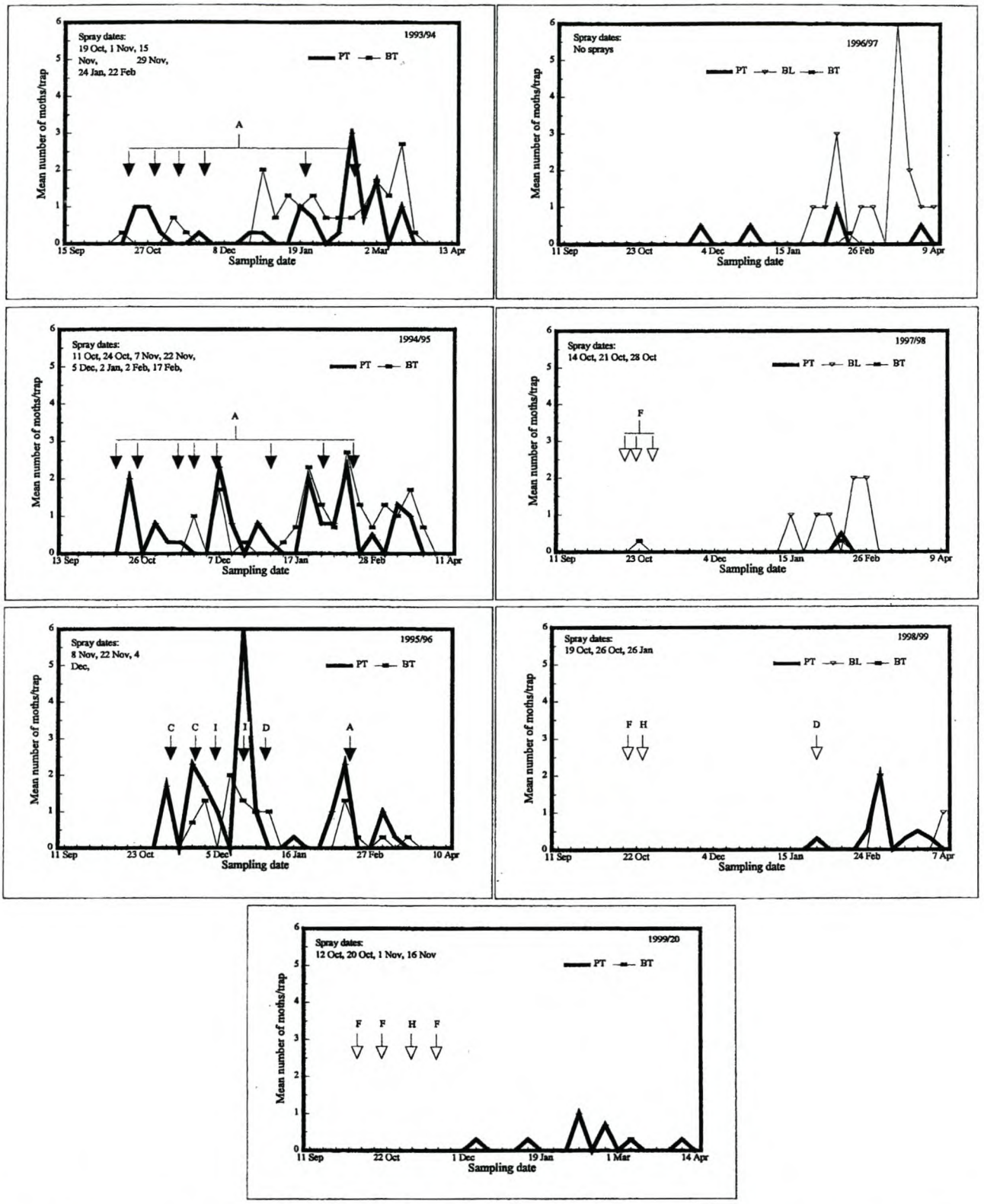

Fig. 3. Number of *Cydia pomonella* moths caught weekly in 10 mg baited pheromone traps (PT) hung high in the tree and bait traps (BT) (1993/94-1999/00) and black light traps (BL) (1996/97 - 1998/99) in orchard G61 of Oak Valley Estates, Elgin. Solid arrows = direct sprays empty arrows = indirect sprays; A = azinphos-methyl; C = flufenoxuron; I = fenoxycarb; D = chlorpyrifos: F = fenvalerate; H = chlorphenapr.

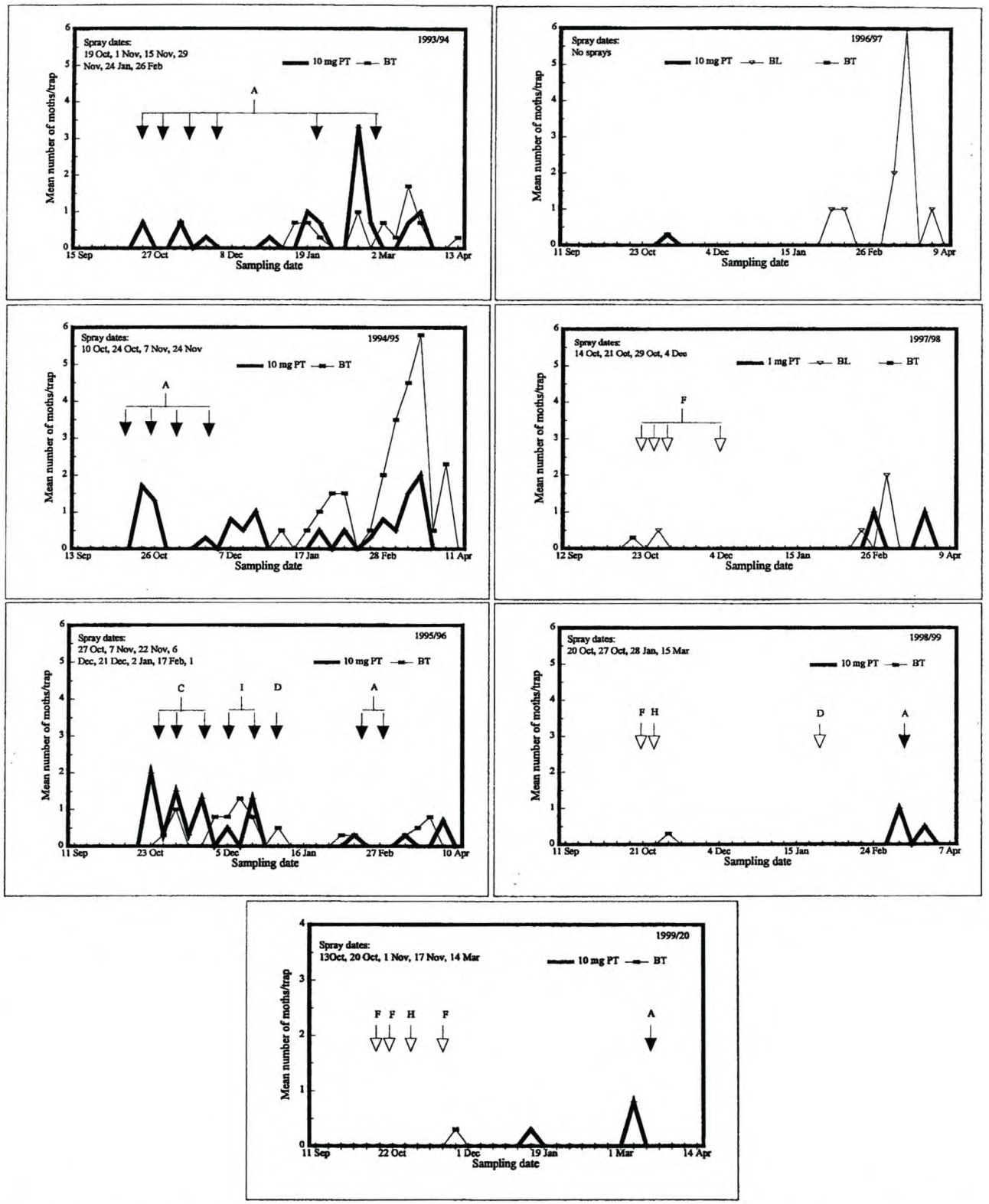

Fig. 4. Number of *Cydia pomonella* moths caught in 10 or 1 mg baited pheromone traps (PT) and bait traps (BT) (1993/94-1999/00) and black light traps (BL) (1996/97-1998/99) in orchard G4T of Oak Valley Estates, Elgin. Solid arrows = direct sprays; empty arrows = indirect sprays; A = azinphos-methyl; C = flufenoxuron; I = fenoxycarb; D = chlorpyrifos; F = fenvalerate; H = chlorphenapr.

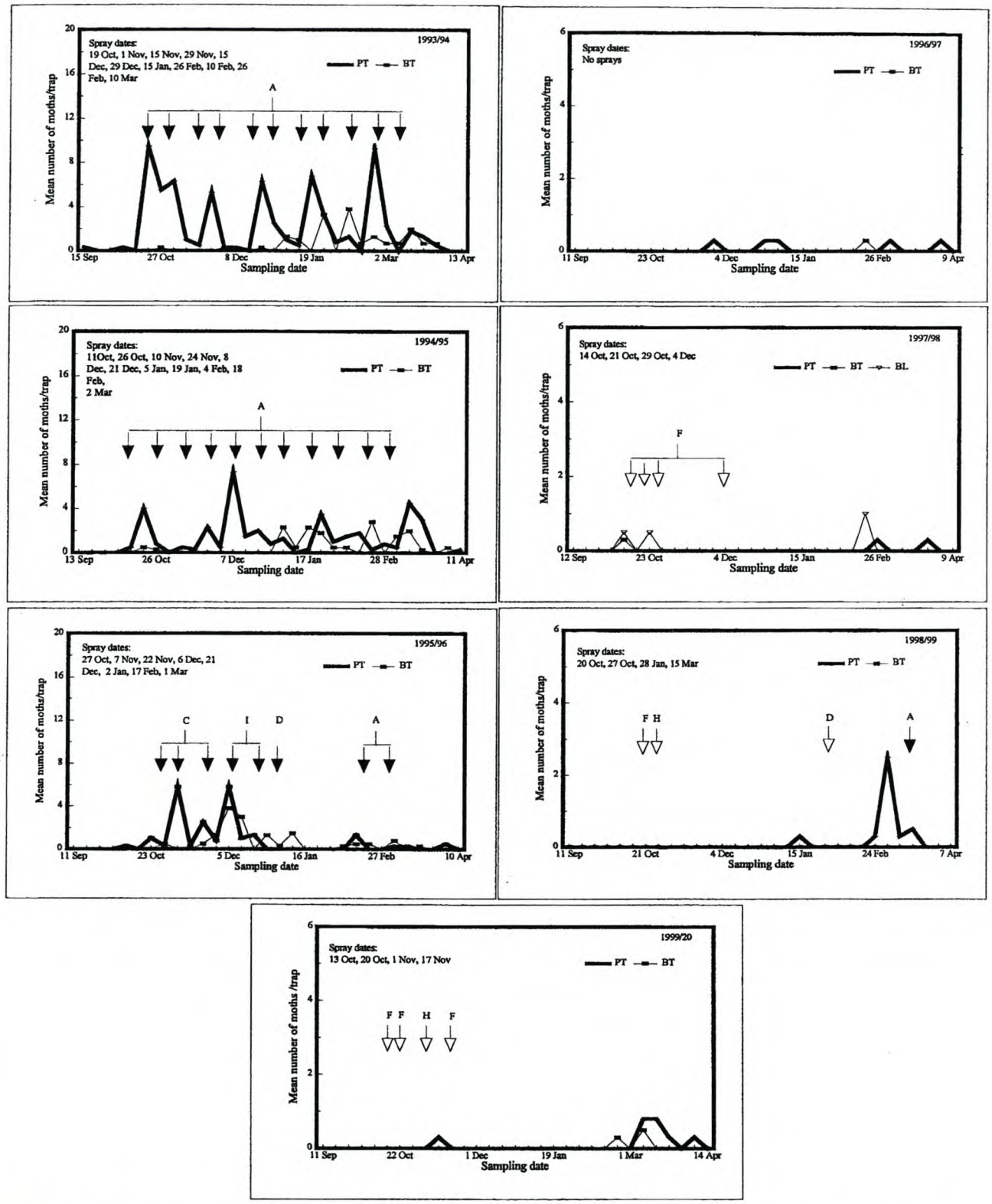

Fig. 5. Number of *Cydia pomonella* caught weekly in 10 mg baited pheromone traps (PT) and bait traps (BT) (1993/94-1999/00) and black light traps (BL) (1997/98-1998/99) in orchard G4B of Oak Valley Estates. Solid lines = direct sprays; empty arrows = indirect sprays; A = azinphos-methyl; C = flufenoxuron; I = fenoxycarb; D = chlorpyrifos; F = fenvalerate; H = chlorphenapr.

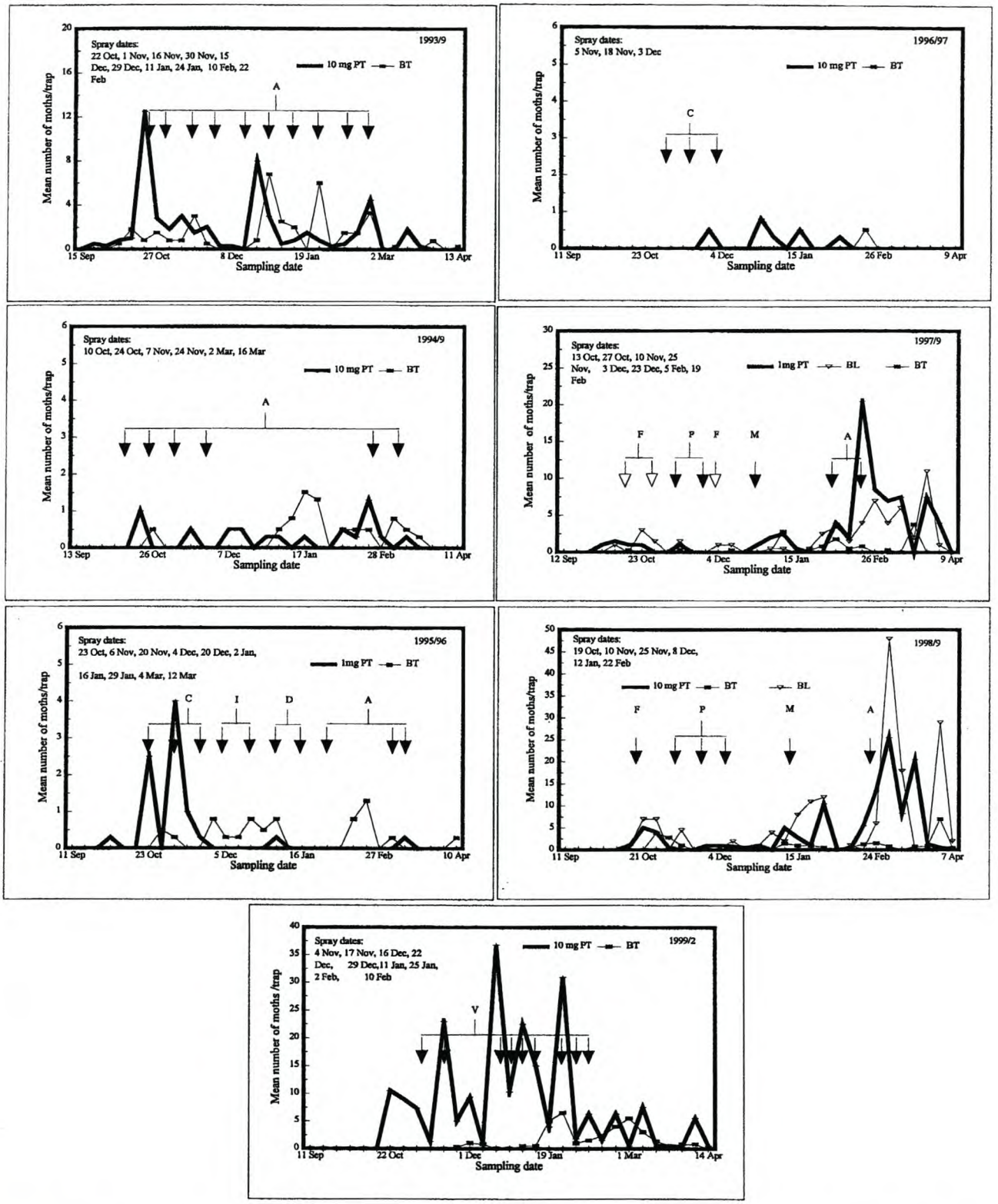

Fig. 6. Number of *Cydia pomonella* caught in 1mg or 10 mg baited pheromone traps (PT) and bait traps (BT) (1993/94-1999/00)and black light traps (BL)(1997/98-1998/99) in orchard W17 of Oak Valley Estates, Elgin. Solid line = direct sprays; empty arrows = indirect sprays; A = azinphos-methyl; C = flufenoxuron; I = fenoxycarb; D = chlorpyrifos; F = fenvalerate; P = methyl-parathion; M = tebufenozide; V = codling moth granulosis virus.

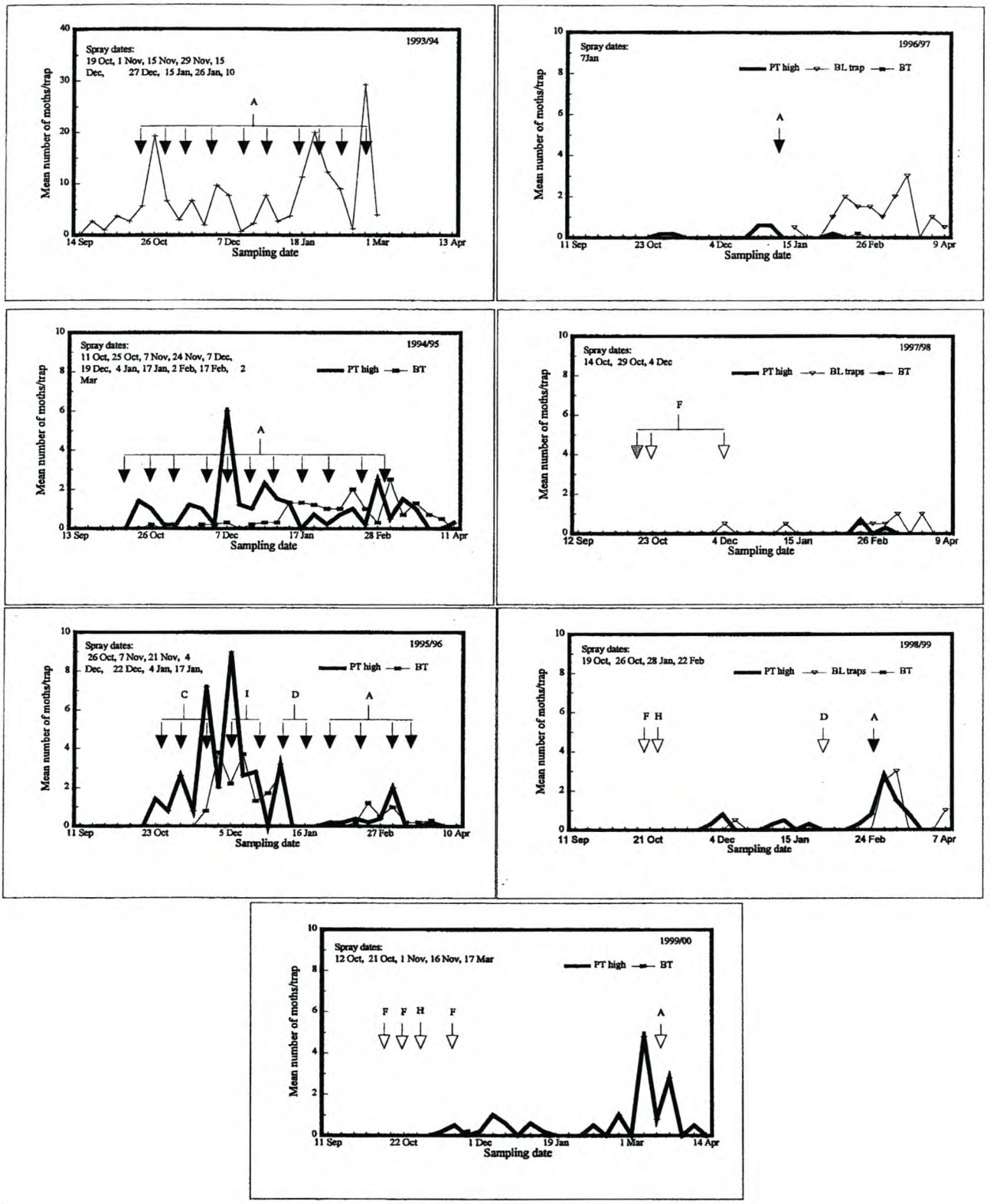

Fig. 7. Number of *Cydia pomonella* moths caught weekly in 1 mg (1993/94) and 10 mg (1994/95-1999/00) baited pheromone traps (PT), bait traps (BT) (1994/95-1999/00) and black light traps (BL) (1996/97 - 1998/99) in orchard G5 0n Oak Valley Estates, Elgin. Solid arrows = direct sprays; empty arrows = indirect sprays; A = azinphos-methyl; C = flufenoxuron; I = fenoxycarb; D = chlorpyrifos; F= fenvalerate; H = chlorphenapr.

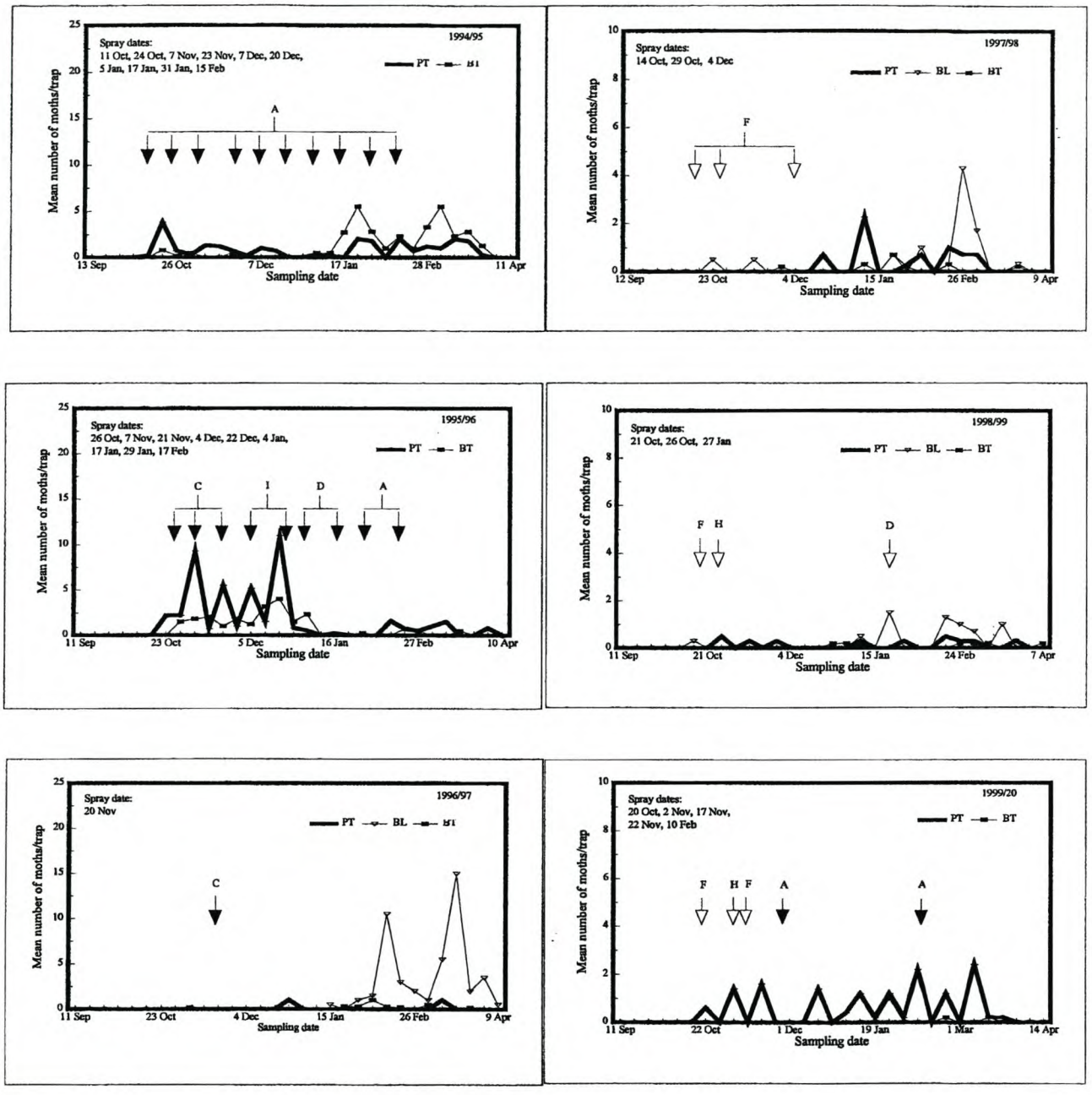

Fig. 8. Number of *Cydia pomonella* moths caught weekly in 10 mg baited pheromone traps (PT) and baited traps (BT) (1993/94-1999/00) and black light traps (BL) (1996/97-1998/99) in orchard G70 of Oak Valley Estates, Elgin. Solid arrows = direct sprays; empty arrows = indirect sprays; A = azinphos-methyl; C = flufenoxuron; I = fenoxycarb; D = chlorpyrifos; F = fenvalerate; H = chlorphenapr.

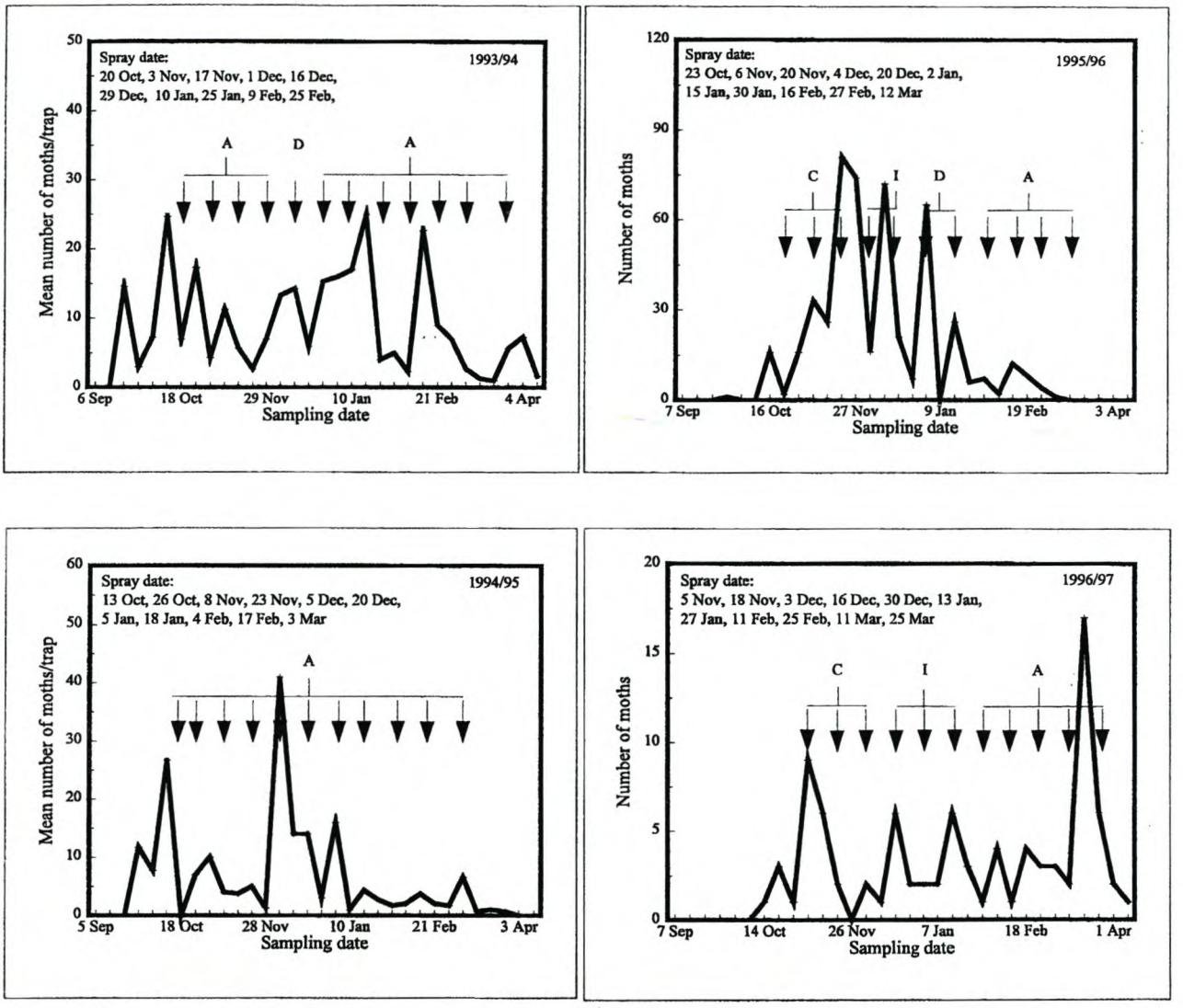

Fig. 9. Number of *Cydia pomonella* moths caught in 1 mg baited pheromone traps in the conventionally treated orchards, W45 (1993/94-1994/95) and A6 (1995/96-1996/97) of Oak Valley Estates, Elgin. A = azinphos-methyl; C = flufenoxuron; D = chlorpyrifos; I = fenoxycarb.

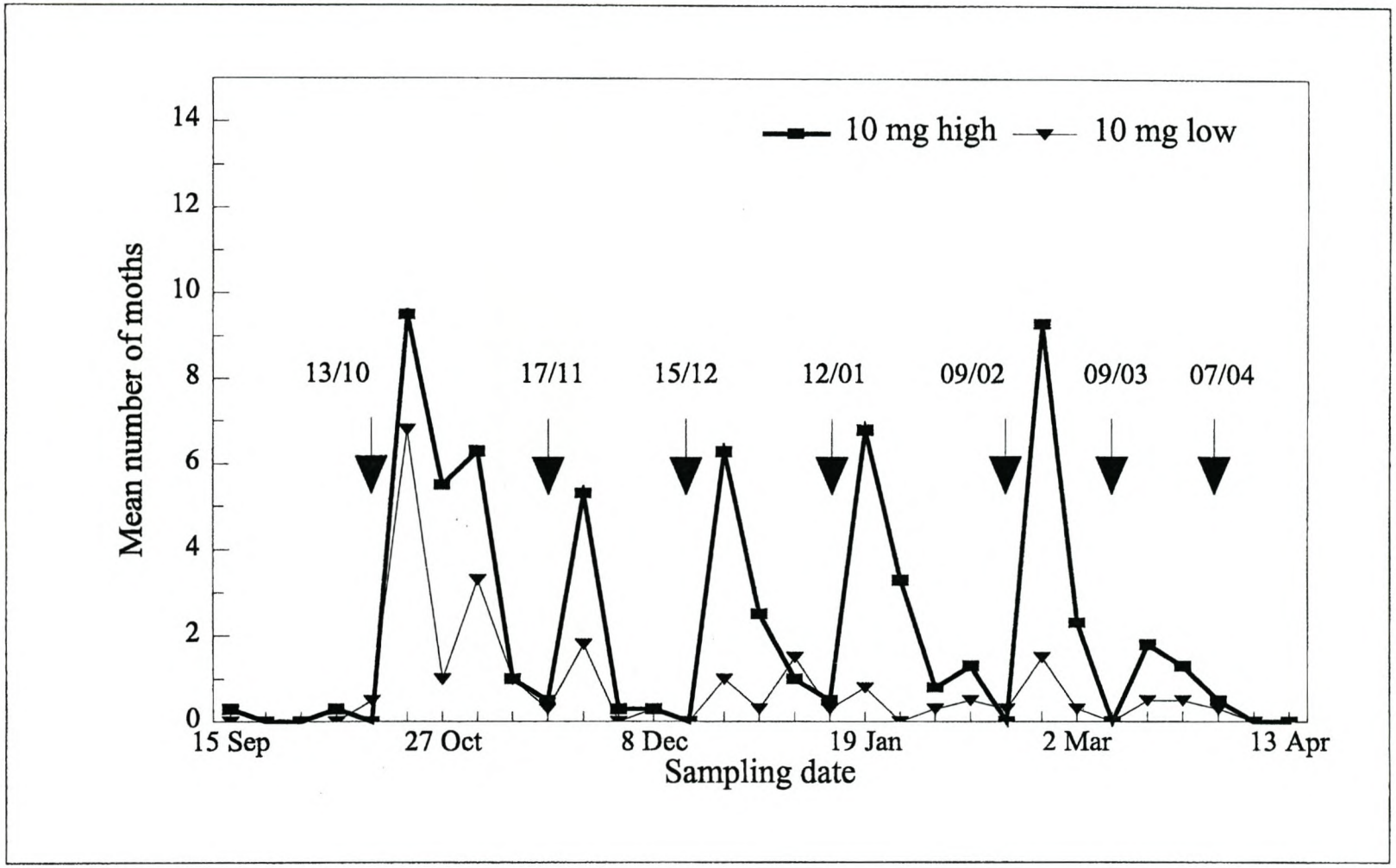

Fig. 10. Number of *Cydia pomonella* moths caught weekly in 10 mg baited pheromone traps hung high and low in the tree in orchard G4B of Oak Valley Estates, Elgin. Arrows indicate lure replacement dates.

5. VALIDATION OF THE CODLING MOTH PHENOLOGY MODEL IN SOUTH AFRICAN POME FRUIT ORCHARDS

ABSTRACT

Codling moth, *Cydia pomonella* (Linnaeus.), is a key pest of pome fruits in the Western Cape, South Africa. Up until the late 1990s the commencement of the codling moth spray programme was based on the full bloom date of the earliest cultivar in the orchard. However, in pome fruit orchards moths emerge before blossom and up to 50 % of first generation moths can emerge, mate and oviposit before full bloom. Consequently full bloom may not necessarily correspond to the commencement of oviposition or first egg hatch. The development of phenology models that incorporate development thresholds and development rates based on degree-days provided a means of accurately predicting biological events such as the initiation of oviposition, first egg hatch of the first flight and commencement of the second and subsequent flights. Although codling moth phenology models are applied in many different apple producing areas of the world the aim of this study was to evaluate the model under South African conditions. The model was evaluated using oviposition, seasonal and egg hatch studies undertaken between the 1983/84 and 1998/99 seasons in Elgin, Western Cape. Using lower and upper development thresholds of 10°C and 32°C, and hourly temperature recordings, the model was evaluated by comparing the number of degree-days accumulated between a selection of three biofixes, and date of first egg hatch. The number of degree-days accumulated from the selection of biofixes to first observed egg hatch varied from 130.7 to 182.2°D. The least variation in the number of degree-days between biofix and first egg hatch was when the second trap catch was used as the biofix. A biofix based on the first evening when the temperature reached or exceeded 17°C at 18:00 after first trap catch also showed less variation than when the biofix was based on first trap catch. In 10 out of 14 observations the model did not differ by more than two days from observed first egg hatch. The mean number of degree-days accumulated between Biofix 2 and first egg hatch was found to be 139.1° D. The mean number of degree-days at which 50 % of the moths of the first flight emerged was 166.6°D, while the mean number of degree-days at which 50 % oviposition occurred was 290°D following biofix. The number of degree-days between the second and third flight biofixes varied between 488.7 and 531.2°D with a mean of 508.1°D. In cooler pome fruit production areas or during years when spring conditions are cool, a saving of up to three sprays can be achieved compared to sprays applied according to the full bloom date.

5.1 INTRODUCTION

Codling moth, *Cydia pomonella* (Linnaeus.), is a key pest of pome fruits in South African and many other countries (Chapman & Lienk 1971; Myburgh *et al.* 1973; Nel 1983; Riedl *et al.* 1998). The biotic potential of codling moth in South Africa is considered to be one of the highest in the world (Myburgh 1980). Infestation commences at petal-fall and continues through three successive generations, and in warm years there can be a fourth generation. Consequently effective control of codling moth requires an intensive control strategy over a period of 7 to 8 months.

The ability to predict events such as the onset of oviposition and first egg hatch allows optimum timing, selection of an appropriate insecticide and reduction in the number of sprays. Although a complex of factors influences the development of the life stages of codling moth (Shelford 1927; Hathaway *et al.* 1971; Riedl & Croft 1978) temperature is considered to be the most important (Wilson & Barnet 1983; Higley *et al.* 1986). The relationship between temperature and development of codling moth was first investigated by Glenn (1922) and more recently by (Riedl *et al.* 1976; Rock & Shaffer 1983; Pickel *et al.* 1986; Pitcairn *et al.* 1991; Kneifl 1992). Glenn (1922) was the first to use degree-days to estimate the development rates for the embryonic and immature stages of codling moth. However, the timing of sprays to coincide with the onset of oviposition or egg hatch can only take place if these events can be accurately determined. Up until the early 1970s fermenting bait pans, essential oils, virgin females and UV light traps were evaluated as monitoring systems that could lead to improved timing of chemical controls for codling moth in relation to oviposition and egg hatch (Borden 1931; Eyer 1934; Nel 1940; Alexander & Carlson 1943; Batiste 1970; Batiste *et al.* 1973). None of these methods consistently provided satisfactory results. This changed with the identification of the sex-pheromone of codling moth, production of synthetic pheromone and lures and the development of sex pheromone traps. For the first time researchers were able to monitor codling moth flight activity more closely and improve and validate the timing of spray treatments based on physiological time parameters (Riedl *et al.* 1976, Beers & Brunner 1992). This lead to the development of predictive models (Geier & Hillman 1971; Croft *et al.* 1976, Brown *et al.* 1978) and the first opportunity of accurately predicting such events as the onset of oviposition and first egg hatch.

Timing of the commencement of the codling moth spray programme is considered an important prerequisite for the effective control of the 1st generation. Codling moth phenology models are

applied in many different pome fruit producing areas of the world. In general codling moth models are based on temperature , daily or hourly maximum and minimum temperatures, which is converted into degree-days. Pheromone traps are used in conjunction with phenology models to obtain a biological starting point for the accumulation of degree-days. The objective of this study was to evaluate the validity of a phenology model under South African pome fruit orchard conditions with respect to:

1. Determination of the biofix.
2. The number of accumulated degree-days (D°) from biofix to first egg hatch using hourly temperatures and a lower threshold temperature for development of 10°C.
3. The risk of fruit damage by not applying a spray at first egg hatch.
4. Determination of the number of °D from 1st biofix to commencement of the second flight.
5. Determination of 50 % moth emergence and oviposition of eggs of the 1st flight.

5.2 MATERIAL AND METHODS

5.2.1 Study sites

Studies were conducted in two orchards, one located on the Elgin Experiment Farm (referred to as Elgin 1) and the other on the Bellvue Experiment Farm (referred to as Bellvue) which is in close proximity to the Elgin Experiment Farm (34.09S and 19.02E) at an elevation of 305 m. The orchard on the Elgin Experiment Farm (Elgin 1) was a 34-year-old orchard, 0.7 ha, consisting of 200 trees with a 6,1 X 6.1 m planting. The trees consisted of 180 Golden Delicious (GD) and 20 Granny Smith (GS) in a 9:1 planting. The orchard on the Bellvue Experiment Farm (Bellvue orchard) was a 14-year-old orchard, 0.9 ha, consisting mainly of GD, GS and Topred (TR) apple cultivars. Elgin 1 was situated at the highest part of the Elgin Experiment Farm and was approximately 341 m above sea level. This orchard was more exposed to the wind than the Bellvue orchard and the fruit in the Bellvue orchard was generally harvested before the fruit in Elgin 1. Both orchards received a full disease spray program and on occasions a single vamidothion spray against woolly apple aphid, *Eriosoma lanigerum*, applied during mid-December. Although insecticide evaluation trials were undertaken in the Bellvue orchard beginning in 1992, insecticide sprays were only applied to less than 10 % of the orchard.

5.2.1.1 Monitoring moth activity

Adult flight activity was monitored daily between 1 September and end-February from 1991 to 1998 with a Pherocon 1C trap hung at head height in the Elgin 1 and Bellvue orchards. An additional Pherocon 1C trap was placed in a conventionally treated orchard on the Elgin Experimental Farm. This orchard is referred to Elgin 2 and was treated with nine high-volume azinphos-methyl sprays. Other than recording moth catches no other observations were taken in Elgin 2. The moth catches in all three orchards are given in Tables 1- 8 together with hourly temperature readings between 16:00 and 19:00, daily wind speed and rainfall.

5.2.1.2 Monitoring egg hatch

When the first Granny Smith trees blossomed in the Elgin 1 and Bellvue orchards, each branch on the tree was meticulously searched for codling moth eggs. Particular attention was focused on the wood surrounding the fruit spur and the leaves of the fruit spur. The position of each egg was marked by encircling the egg with water-proof black ink and marking the position of the egg on the branch with a plastic tag. The stage of development of each egg was recorded as opaque, red ring or black spot. The eggs were inspected every second to third day until the black head stage of development was observed. Thereafter the eggs were inspected daily except in the Elgin orchard in 1992 and 1996 and the Bellvue orchard in 1994 and 1997. On these occasions eggs were only inspected every second day and first egg hatch was recorded as occurring on the day previous to the first observed egg hatch. After the first eggs hatched they were inspected every second to fourth day to determine percent egg mortality. The number of eggs observed in each orchard varied from 30 to 104. Hourly temperature data were obtained from an automated weather station on the Elgin Experiment Farm. The Elgin and Bellvue orchards were approximately 400 m and 800 m respectively from the weather station. Although reference is made to first egg hatch, this refers to the eggs under observation and not necessarily to egg hatch of the first egg laid in the orchard. However, all attempts were made to find the first eggs laid. Because of the erratic trap catches in spring (September/October) the accuracy of the degree-day phenology model was evaluated by comparing the number of degree-days accumulated between a selection of three biofixes, and the date of first egg hatch.

5.2.1.3 Biofixes and degree days

Biofix 1 was based on first moth catch, Biofix 2 was second trap catch and Biofix 3 was based on the first evening when the temperature reached or exceeded 17°C at 18:00 after Biofix 1. The number of degree-days required to complete development was calculated using the sine-wave model (case 3) of Baskerville & Emin (1969), based on hourly maximum and minimum temperatures and a lower and upper development threshold of 10°C and 32°C respectively.

5.2.1.4 Seasonal occurrence

The seasonal occurrence of codling moth was obtained from studies undertaken in the Elgin orchard between the 198384 and 1989/90 seasons. Corrugated cardboard strips were placed around the trunk and lower branches of 10 Granny Smith trees. The bands were inspected weekly for mature fifth instar larvae emerging from the fruit. The larvae were counted, placed in gauze bags and kept in two cylindrical gauze containers suspended from branches in the orchard. The bags were inspected weekly to determine moth emergence which would reflect the actual emergence from natural cocooning sites. From the seasonal occurrence and oviposition studies (Chapter 1), biological events such as 50 % moth emergence and oviposition of the first flight and commencement of the second flight were determined in terms of degree-days.

5.2.2 Statistical analysis

A 2 x 3 factorial experiment with seven replications (years) in a complete randomized design was done. The factors were two farms (Elgin and Bellvue) and three biofixes (first moth catch; second moth catch; first evening when temperature reached or exceeded 17°C after Biofix 1). Student's T-LSD were calculated at the 5 % level to compare treatment means. Moth emergence and oviposition between the 1985/86 and 1988/89 seasons were defined on a degree-day (°D) scale. Simple linear regression of probit emergence on log °D and probit oviposition on log °D were used to determine 50 % emergence and oviposition. This was used as an empirical analysis as least squares regression was used on these repeated measures, ninary data. A more appropriate analysis would have been a repeated measures maximum likelihood regression. However the availability of suitable software precluded this. The same method was used by Riedl *et al.* (1976) to analyse moth emegence and oviposition data. The moth emergence and oviposition data for the summer generations was not analysed as there was too much overlap between the summer generations (Figs 1-2).

5.3 RESULTS

5.3.1 Monitoring moth activity

In some years oviposition was very low and it was difficult to find eggs, particularly in the Elgin 1 orchard. This is attributed to this orchard being situated on the highest part of the farm and more exposed to wind than the Bellvue orchard. The greater difficulty of finding eggs in this orchard during the spring period is attributed to the disruptive and cooling effect of the wind on moth activity such as mating and oviposition. The Pheromone trap catches of codling moth in the Elgin 1 and Bellvue orchards showed that first trap catch was recorded between 2 September and 10 October between 1991 and 1998, a period of 38 days (Tables 1 to 8). In general trap catches tended to be low and very irregular at the commencement of the spring flight. Male moths were recorded on evenings when the temperature was 17°C and lower at 18:00. This occurred in the Elgin 1 orchard during 1991 when the first and the second trap catches were recorded in traps on evenings when the temperatures at 18:00 were 9.5°C and 13.4°C respectively. Between 17 and 28 September 1991 the temperature did not rise above 17°C at 18:00.

During 1992 the temperature between 14 September (first trap catch) and 26 September reached or exceeded 17°C at 18:00 on only two occasions, although on several evenings the temperature almost reached 17°C. During this period most moths were recorded in traps on those days when the previous evening temperature exceeded 17°C except on 24 September when the previous evening's temperature was 13.0°C at 18:00 (during spring moths recorded in traps were from the previous evening). Similar trends in the trap catches were also observed between 1993 and 1998. The most positive biofix was recorded in October 1996 when all three pheromone traps recorded consistent catches from 10 to 30 October. Despite the low and intermittent trap catches, the date of the first trap catch in seven of the eight years were very similar for the two unsprayed orchards, varying by not more than 5 days. In 1995 the difference in the dates of the first trap catches between the Elgin and Bellvue orchards was 14 days. The first moths were caught from 28 to 47 days and 24 to 37 days before full bloom of the GS and GD trees respectively. The trap catches from the sprayed orchard were considerably lower and more erratic.

5.3.2 Egg hatch, biofixes, and degree-days

Percentage hatch of the eggs laid by the first moths of the spring flight varied considerably between years. In the Elgin orchard it varied from 18.2 % (1992) to 77.7 % (1996), and in the Bellvue orchard from 28 % (1997) to 93.1 % (1996) (Table 9). Mortality of eggs was due mainly to infertility, desiccation, and wind and rain dislodging eggs from leaf surfaces. Egg hatch could increase rapidly over a relatively short period of time (Tables 10 and 11).

Based on hourly temperature readings the number of degree-days accumulated from a biofix of first trap catch to first egg hatch varied from 130.7 to 179 °D for the Elgin orchard (Table 12) and from 139.2 to 177.2 °D for the Bellvue orchard (Table 13). The number of degree-days obtained in this study is more than the 121.4 °D (degree-days for pre-oviposition and eggs to hatch) obtained from Table 1, Chapter 2. The developmental studies done in the laboratory are undertaken under controlled conditions while in the orchard conditions are very variable. The least variation in the number of degree-days between biofix and first egg hatch was obtained when the second trap catch was used as the biofix. No significant interaction between orchards and biofix was found ($P = 0.704$), therefore main effect for biofixes was compared which was found to be significant ($P = 0.035$) (Table 14). The mean number of degree-days accumulated from Biofix 1, 2 and 3 to egg hatch was 154.4, 139.1 and 144.2 °D respectively . There was a significant difference between Biofix 1 and 2. No significant differences were found between Biofix 1 and 3, or between 2 or 3 (Fig 1).

The date of first egg hatch was compared to the full bloom dates of the GS and GD trees in both orchards (Table 15 and 16). The full bloom date of the GS trees is the stage when most growers apply their first codling moth spray. There were variations between the two orchards with respect to the timing of sprays based on the full bloom date of both cultivars compared to first egg hatch and the model prediction. In both orchards the GS full bloom date was from 3 to 15 days earlier than first egg hatch in 12 out of the 14 observations. Only in 1992 and 1994 did full bloom occurr 2 and 4 days after first egg hatch respectively in the Bellvue orchard (Table 16). The full bloom date of the GD cultivar varied from 8 days before to 7 days after first egg hatch in the two orchards (Table 15 and 16). In the Belluve orchard the full bloom date of the GD trees was later than first egg hatch in 4 out of the 7 observations.

In the case of the phenology model there was less variability between predicted and observed first egg

hatch for all three biofixes excluding the Bellvue orchard in 1995. The latter was due to a period of 9 days between the first and second trap catch. Sprays based on the first trap catch would have resulted in the spray being applied 12 days earlier than necessary. Using the second trap catch as the biofix, predicted first egg hatch varied from 5 days earlier to 4 days after observed first egg hatch in the Elgin and Bellvue orchards. In 10 out of 14 observations the model did not differ by more than 2 days from observed first egg hatch. During 1993, in which a warm spring period was experienced, the full bloom date in the Elgin and Bellvue orchards was 3 and 1 day earlier than first egg hatch. At this stage of the season the mean diameter of 72 fruit in the vicinity of where the first eggs emerged was 0.9 mm.

The curves for cumulative moth emergence and oviposition between the 1985/86 and 1988/89 seasons are given in Fig 4 . Degree-day accumulations commenced from Biofix and the log-probit equations are given in Table 18. The r^2 values for emergence and oviposition ranged from 0.86 to 0.98 which indicated a good fit of the probit lines to the data sets. The mean number of degree-days to 50 % emergence and oviposition are also provided. The 50 % moth emergence varied from 137.1°D in 1985 to 233.7°D in 1987 with a mean of 189.8°D, while the 50 % oviposition varied from 291.7 to 357.3°D with a mean of 330°D.

5.3.3 Seasonal occurrence

From the seasonal occurrence studies undertaken between the 1983/84 and 1989/90 seasons mature 1st generation 5th instar larvae started leaving the fruit during the second half of November. From these studies it was not possible to establish when 1st generation larvae stopped emerging from the fruit and 2nd and 3rd generation started leaving the fruit. However, low numbers of 3rd generation larvae continued to emerge from the fruit during April and May (Figs 2 and 3). In general first generation moths started to emerge in September, only during the 1984/85 season were 1st generation moths recorded emerging in August (Table 17). Although the first generation flight tended to decline toward the middle of December low numbers of 1st generation moths were recorded emerging in January during the 1987/88 and 1989/90 seasons (Figs 2 and 3). Between the 1983/84 and 1989/90 seasons the biofix varied between 22 August and 22 September, a period of 31 days. In four out of the 7 years the biofix occurred between 11 and 22 September. Generally the second flight commenced

in December, only in the 1985/86 season did the second flight commence toward the end of November (Table 17). The second and third flights could not be separated, making it difficult to determine the commencement of the third or fourth flights from seasonal moth counts (Figs 2 and 3). Moths stopped emerging between the middle to end of March in the unsprayed apple orchard. In commercial orchards the moths can still be active in the first half of April (Chapter 3, Fig.9). Oviposition in the summer months followed the moth emergence more closely in the 1985/86 and 1988/89 seasons but tended to lag behind moth emergence in 1986/87 and 1987/88 seasons (Fig. 5). Eggs were recorded from October to the beginning of April. The number of degree-days between the first and second flight biofixes varied between 531.2 and 488.8 °D with a mean of 508.1 °D. Based on the number of degree-days between the first and second flight biofixes the third flight was estimated to occur between 22 January (1985/86) and 10 February (1989/90). During the 1985/86 season it is probable that there was a fourth flight starting on 10 March 1996 (Fig 2). To determine the percentage of first generation larvae entering diapause the mid-point of the trough between the first and second generation larval emergence curves was taken as the end of first generation larvae leaving the fruit (Figs 2 and 3). The number of first generation larvae entering diapause varied between 1.8 % and 16.5 % with a mean of 8.7 %. Up until 20 January, the number of larvae entering diapause per week seldom exceeded 10 %. Approximately 50 % of larvae emerging from the fruit between 6 February and 13 February entered diapause and by the end of March all larvae had entered diapause (Fig 6.).

5.4 DISCUSSION

Although the present studies were undertaken in unsprayed apple orchards supporting high codling moth populations, trap counts at the commencement of the spring flight tended to remain very low and irregular, making the accurate determination of a biofix difficult. On occasions first trap catch was followed by periods of 3 to 9 days of no moth catches. This has also been observed by Beers *et al.* (1993). The low and intermittent trap catches at the beginning of the spring flight was attributed to the low temperatures during spring although other factors, such as wind and rain, could also have affected catches of male moths in pheromone traps (Borden 1931; Rothschild 1982; Riedl *et al.* 1986; Pitcairn *et al.* 1991). Riedl *et al.* (1986) provided a literature review of the effect of temperature on male flight and concluded there was no general agreement on the lower threshold temperature for

flight. In their review the authors concluded that the lower temperature for male flight varied between 11.0° C and 16 °C. Riedl *et al.* (1986) reporting on unpublished studies in the laboratory, found the first male moths commenced flying at 11°C, 50% by 14°C and all moths were recorded flying by 18°C. The optimum temperature range for male flight was given as 18°C to 26°C. More recently Pitcairn *et al.* (1990) showed that the lowest temperature at which flight was observed was 12.01°C, with most male moths being trapped when the mean evening temperature was greater than 15.8°C.

The reliability of a codling moth phenology model is primarily dependent on obtaining an accurate biofix and temperature data. Of these two requirements determining a valid biofix is considered the most difficult in view of the erratic trap catches. For this reason the biofix has been defined in a number of ways. The biofix has been defined as the first male moth or moths trapped with no significant interruption in trap catches thereafter (Riedl & Croft 1978); first consistent or large (3-4) catch in an evening (Brunner *et al.*1982); first sustained capture of male moths in pheromone traps (Beers & Brunner 1992). Beers & Brunner (1992) have reported that in some instances populations in commercial orchards are so low it is impossible to establish a valid biofix. Beers *et al.* (1993) described the biofix more fully as the date when several moths are caught in a single trap in an evening or when the majority of the traps in a given area trap moths on the same night. The difficulty is determining the meaning of "consistent or sustained moth catch" and whether "consistent catch" necessarily implies that mating is taking place in the orchard. According to Anon (1991) first catch in the central valley of California usually occured when the sunset temperature was 17°C or higher, with mating only taking place at 17°C and higher. Although matings in the spring period have been observed to occur between 15°C and 20°C few moths were observed mating below 16°C with peak mating occurring at 17°C (Chapter 2). Very little oviposition occurred below 16°C. Most moths were mated between 18:00 and 19:00, when sunset was at 18:30. In the present study a number of male moths were recorded in the traps on evenings when the temperature was 16°C or lower at 18:00 suggesting that male moths were active, but this was not necessarily an indication that mating was taking place in the orchard. In view of the time of day and temperature at which male moths fly and mate the selection of an accurate biofix could possibly be more easily achieved by also considering, together with trap counts, the temperatures between 17:00 and 19:00. Thus the first catch was also evaluated as a biofix as moths were trapped on evenings when the temperature was above 17°C and consequently mating could have taken place. This occurred in 12 out of the 14 first trap catch biofixes. However, although the temperature was above 17°C it may have been above 17°C for too

short a period for mating to have taken place as the evening temperature can drop rapidly after sunset. In addition other factors such as rain or wind could have influenced mating or oviposition.

On several occasions the selection of a biofix that appeared to conform to the definitions of "first consistent catch" or "first large catch in an evening" did not necessarily provide a good biological reference point for accumulating degree-days and predicting first egg hatch. This phenomena was observed to occurred in the Elgin orchard in 1993 (Table 3). The first catch (3 September) was followed by three evenings when the temperature barely rose above 15°C at 18:00. The second catch was recorded on 7 September (caught on the evening of 6 September), when the evening temperature on 6 September rose above 17°C at 18:00. All three traps recorded moths on 7 September with four moths being recorded in Elgin 1. Using the second catch as the biofix the spray applied according to the phenology model would have been 5 days earlier than first egg hatch. A more accurate biofix would have been between 11 and 12 September (143.8-139.9°D after biofix). It is probable that codling moth activity was lower in this orchard than expected. This was possible due to a daily wind speed of 3.5 and 3.9 m/s on 9 and 10 September respectively with rain on 10 and 11 September. The temperature on 10 (11.7°C) and 11 (13.0°C) September was also very low at 18:00. These weather conditions are known to have a negative impact on mating and oviposition (Batiste *et al.* 1973; Borden 1931; Rothschild 1982; Riedl *et al.* 1986; Pitcairn *et al.* 1991). Although oviposition can take place at an earlier time of the day than mating (Chapter 2) the cool and windy conditions could have prevented oviposition or reduced the level of oviposition taking place, making it difficult to find the first eggs laid.

The biggest difference between the observed and expected egg hatch occurred in the Bellvue orchard in 1995 (Table 16). In this year there was a 11 to 12-day difference in the timing of the first codling moth spray when the biofix was based on either the first or third biofix. Between the first and second biofixes the temperature rose above 17°C at 18:00 on several occasions reaching a high of 24°C on 14 September (Table 5). During this period it rained only on one occasion, 11 September, and the average wind speed between 14:00 and 19:00 varied between 1.2 and 2.7 m/s. There was also a difference of three days with no moth catches between the second and third trap catches, although the temperature rose above 17°C at 18:00 on two consecutive days of the three days (Table 5). The second trap catch provided the best biofix, the timing of the first codling moth spray being one day too late.

In the present study the timing of sprays based on the full bloom date of the GS cultivar varied over a 19-day time period with sprays being timed 15 days earlier and up to 4 days after first egg hatch. In the Elgin orchard the GS full bloom date was approximately a fortnight before egg hatch in 1995 and 1996. By timing the commencement of the codling moth spray programme on the full bloom date an extra insecticide spray would have been applied in these two years. This would not only have increased the cost of the codling moth control programme but would also have led to the exposure of beneficials and the orchard environment to an unnecessary insecticide treatment. However, where producers do not have access to a phenology model the GS full bloom date as the cue to commence the codling moth spray programme in apple orchards will result in sprays being applied earlier than later in most years (Table 15 and 16). Only in the Bellvue orchard would sprays have been applied too late, i.e. two and four days in 1992 and 1997 respectively. Therefore, for those producers who do not have access to temperature data the GS full bloom date is a "safe" cue to commence the codling moth spray programme in apple orchards. This corresponds with the findings of Beers & Brunner (1992), who observed the calender method (first codling moth spray applied 21 days after full bloom) as being up to 18 days earlier than observed first entry. The model timing (accumulation of 139°D from biofix to 3 % egg hatch) did not differ by more than two days from the first observed fruit entry by newly hatched larvae.

When using first trap catch as the biofix the phenology model would have resulted in 13 of the sprays being applied 0 to 7 days before egg hatch (Table 15 and 16). The use of the second trap catch as the biofix resulted in the model timing (139°D to first egg hatch) differing by only two days in 10 out of the 14 observations from first observed egg hatch. Beers & Brunner (1992) found that the model timing was 100 % accurate in five years out of nine and never differed by more than two days from observed first fruit entry. In the present study the model was 100 % accurate five years out of 10 when the second trap catch was used as the biofix.

The results have shown the phenology model to be more accurate than the full bloom date in synchronizing the timing of the first codling moth insecticide treatment to coincide with first egg hatch. Although the number of degree-days accumulated between second trap catch and first egg hatch varied from 127.9 to 164.0 for the Elgin and Bellvue orchards, nine of the 14 observations varied between 132.7 and 144.1 °D. However, degree-day intervals can vary from area to area (Croft & Riedl 1991) and orchard to orchard. The Bellvue orchard was more protected than the Elgin

orchard and egg hatch was generally earlier in the Bellvue orchard. It was also easier to find eggs in this orchard suggesting that oviposition was higher due to more favourable oviposition conditions or because of a higher overall codling moth density in this orchard compared to Elgin. This is probably a reflection of slightly warmer conditions. Although it would be ideal to have temperature data from each orchard, or different areas of the farm that are considered climatically different, this is impractical. However, the similarity of the results from this study and those of Riedl & Croft (1978) and Beers & Brunner (1992) suggests that a degree-day accumulation of 139 °D between biofix and first egg hatch will provide an accurate means of determining the commencement date of the codling moth spray programme.

Under South African climatic conditions a one day delay in the timing of the spray can result in an egg hatch of between 1.0 % to 31.1 %, and a 4-day delay 10.6 % to 40.0 %. In 1996 the percentage hatch in the Bellvue and Elgin orchard was 92.2 and 55.6 eight and six days after first egg hatch respectively. However, only in the Elgin orchard in 1995 and in the Elgin and Bellvue orchards in 1996 was the percentage hatch exceptionally high. In the study undertaken by Beers & Brunner (1992) percentage hatch after first egg hatched occurred at a slower rate than in South Africa. A delay of six days in the insecticide application, due to adverse weather conditions (high winds), could result in a 33 % egg hatch before insecticides application (Beers & Brunner 1992). Under South African conditions 70 % egg hatch occurred only six days after the first egg hatch. This difference is probably due to cooler spring conditions in Wenatchee, Washington State.

On two occasions in the Bellvue orchard the GS full bloom date was after egg hatch. In 1992 and 1997 full bloom was two and four days after egg hatch respectively. However, egg hatch was relatively low during these two years. In 1992 egg hatch was between 6 % and 7 %, 1 to 3 days after first egg hatch, while in 1997 it was 5.6 % four days after first egg hatch. Although percentage egg hatch can increase very rapidly, the percentage mortality of the first eggs laid can be as high as 85 % (Table 9). Furthermore, under commercial conditions the mortality of the first larvae to emerge is probably high due to factors such as natural fruit drop, chemical and hand thinning, mortality of first instar larvae due to rain, predation and other natural factors. Of the first eggs to be laid by moths of the spring flight only a small percentage probably survive and therefore a delay of 3 to 4 days in the spray application is probably not critical. Furthermore, under commercial conditions the commencement of the codling moth spray programme is based on the first orchard(s) to give a biofix.

This results in many orchards being sprayed well before first egg hatch. Generally growers also commence the spray programme a day before predicted egg hatch to be on the "safe side".

The areas that would benefit the most from the implementation a phenology model are the cooler apple and pear production areas and when cool spring conditions prevail (Table 19). The full bloom date of Forelle pears (the earliest blossoming cultivar) were compared to the model timing in a cool (Koue Bokkeveld) and warm (Warm Bokkeveld) pome fruit production area between 1994 and 1996. The 1994/95 season was a warm season whereas the 1995/96 and 1996/97 seasons were cool, particularly the early part of the season. In the Koue Bokkeveld the model timing varied between 31 and 42 days later than the full bloom date. By applying sprays according to the phenology model between 2 and 3 sprays would have been saved. In the Warm Bokkeveld the difference between the full bloom date and model timing was only 8 days in 1994. However, in 1995 and 1996 the model timing was 26 and 38 days later than the full bloom date respectively as a result of cooler conditions. Up to two sprays could have been saved during these two years.

The first trap catch should possibly be selected as the biofix if the interval of no catches between the first and second moth catch does not exceed three days and the temperature remains above 17°C at 18:00 for any two of the three days. Where the interval between the between the first and second trap catch exceeds four or more days the second trap catch should be chosen as the biofix. To ensure that the time interval between the first moths emerging in the orchard, and being trapped in the pheromone trap, is as accurate as possible it may be favorable to increase the number of traps from 1 to 4. Although fruit growers are unlikely to increase the trap density from the recommended 1 trap per 2 ha on their farm it is recommended that in 3 to 4 orchards that are known to have the highest populations on the farm the trap density should be increased to four traps and monitored on a daily basis.

Although this study has shown that the commencement of an insecticide programme can be accurately timed to coincide with first egg hatch by means of a phenology model, it was supplemented by observations on the seasonal occurrence, oviposition and egg hatch to further our understanding of codling moth behaviour and subsequently also the management of this pest throughout the season. It appears that there are probably no full generations of codling moth in the Western Cape, but 3 to 4 partial generations per season. Progressively more larvae of each generation enter diapause until

all the larvae resulting from the last flight enter diapause. It is questionable whether codling moth has two complete generations in Washington as reported by Beers & Brunner 1992. Over the seven year study period there was a relatively small area of overlap between the first and the second generation moth flights (Figs 1and 2). Although some moths of the first flight emerged during December and even into January the numbers were very low, comprising between 1.4 % and 11 % of the population. There was less overlap between the first and second generations than between the summer generations.

The main problem with respect to the control of the eggs and neonate larvae that originate from the spring flight is that the moths start to emerge 5 to 8 weeks before blossom and emerge over a period of 13 to 20 weeks. The second and third generations extended over a much shorter period of only 13 to 17 weeks. Egg hatch on the earliest blossoming apple cultivar, Granny Smith, has been shown occur prior to and during the blossom period. The oviposition and seasonal studies indicate that 50 % moth emergence can occur up to 51 days after biofix and 50 % oviposition 28 days later when most of the moths have emerged (Table 17). The extended period between 50 % moth emergence and 50 % oviposition is probably a reflection of the cooler evening temperatures during this period reducing the number of eggs laid per evening and extending the oviposition period of each female. Riedl & Croft (1978) showed that trap catches decline and are lowest when peak first generation oviposition occurs. Based on a minimum incubation time of 82.2 °D (Chapter 2), 50 % egg hatch would probably have occurred on 17 November and 4 December during the1985/86 and 1988/89 seasons respectively. The fact that 50 % oviposition and egg hatch can occur some time after 50 % moth emergence should be taken into account when managing the first flight of codling moth. Considerable egg hatch can still be taking place one to two weeks after 50 % egg hatch when trap counts have probably decreased and the risk of infestation is not perceived to be not critical. During the spring period there are periods of unfavourable weather conditions, such as wind that may delay spraying. It is important that the spray interval should not be extended during these periods. The delay of sprays at peak egg hatch periods will result in unacceptable levels of infestation. The study indicates that maximum oviposition occurred during the month of November, making this month a critical period for codling moth management. In those situations where traps toward the end of the previous season indicated a build-up in moth counts and this is not reflected by the spring trap counts in the following season, particularly in mating disruption orchards where traps are not as reliable as in conventionally treated orchards, it may still be advisable to apply control actions during November.

The present study has shown that the first moths of the second flight can be expected to commence emerging at a mean of 508 °D after the first biofix. The first moths of the second generation to emerge probably represent the fastest individuals within the population This figure is very similar to the minimum number of degree-days of 505 required to complete a generation given in Chapter 2. The 505°C was obtained using a lower threshold temperature of 10°C and the five fastest development times for each replication of each life stage at constant temperatures. In a publication produced by the University of California it is stated that the second generation could start as early as 413 °D after the first biofix, although second flight was generally detected between 500 and 589 °D after the first biofix (Anon 1991). Riedl & Croft (1978) presented a minimum mean generation time of 525 degree-days, based on the results of Glenn (1922). The minimum generation time of 5258C was based on the egg, larval and pupal stages.

This study has shown that under South African orchard conditions the model used in combination with pheromone trap counts and seasonal moth emergence and oviposition data can be an indispensable aid in accurately determining key events in codling moth biology. These events are the commencement of first egg hatch of the first codling moth generation, commencement of each of the summer flights, and periods of maximum ovipostion and egg hatch. The development of resistance to azinhos-methyl and pyrethroids in South Africa (M. Addison, *pers comm.*) and the very real threat of resistance and cross-resistance to the presently limited insecticides available to control codling moth in the South Africa, highlights the importance of this model as a much needed tool to accurately schedule control actions and reduce the number of insecticide sprays. This is particularly so in the cooler pome fruit producing areas of the Western Cape. Codling moth management of the future will be based more and more on information management and the precise utilization of the information to achieved maximum control with minimum insecticide intervention. This model will be one of the methods used to generate such information.

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Table 1. Pheromone trap catches of *Cydia pomonella* in the Elgin and Bellvue orchards on the Elgin and Bellvue Experimental Farms in September 1991. Hourly temperatures between 16:00 and 19:00, daily wind speed and rainfall were obtained from the weather station on the Elgin Experimental Farm.

Date (Sept)	Trap			Temperature (°C)				Daily wind speed (m/s)	Rainfall (mm)
	Elgin 1	Elgin 2	Bellvue	16:00	17:00	18:00	19:00		
1	0	0	0	20.7	18.4	14.8	12.1	0.4	0
2	0	0	0	24.0	21.2	16.2	13.4	0.4	0
3	0	0	0	15.1	13.6	12.1	11.9	1.3	0
4	0	0	0	12.8	11.2	11.2	11.5	3.0	18.2
5	0	0	0	11.3	11.0	10.1	10.5	1.5	0
6	0	0	0	13.0	12.0	10.0	9.8	2.4	0.8
7	0	0	0	9.5	9.1	6.8	6.9	2.7	25.1
8	0	0	0	9.5	9.5	9.5	9.6	3.6	9.3
9	0	0	0	11.6	10.9	10.5	10.0	1.9	16.6
10	0	0	0	15.0	13.6	12.2	12	6.7	0
11	0	0	0	17.3	15.9	13.6	12.0	0.7	0
12	0	0	0	18.4	16.3	15.1	14.4	0.5	0
13	0	0	0	13.7	13.5	13.2	13.2	0.3	4.2
14	0	0	0	15.6	15.1	13.8	13.0	0.7	0
15	0	0	0	11.7	12.2	12.5	12.6	3.9	21.0
16	0	0	0	12.7	13.5	13.3	13.5	2.5	0
17	0	0	0	15.9	14.1	12.8	12.0	2.9	0
18	0	0	0	9.4	9.8	9.5	9.3	3.0	17.3
19	1	0	0	12.0	11.0	9.5	8.3	0.7	2.4
20	0	0	0	14.4	12.8	11.2	9.0	0.6	0
21	1	0	0	17.9	16.1	13.4	11.2	0.4	0
22	0	0	1	20.9	18.6	16.7	15.3	0.5	0
23	1	0	0	16.0	15.0	13.0	12.0	1.2	0.4
24	0	0	0	15.1	13.5	12.4	12.1	1.4	0
25	0	0	3	18.2	16.9	15.6	14.8	1.1	0
26	10	0	0	15.5	14.5	13.7	13.8	1.7	0.2
27	1	0	0	13.7	14.1	13.6	13.4	2.6	3.8
28	1	0	1	13.3	13.8	13.7	13.3	0.7	0
29	1	0	4	23.6	21.5	19.1	16.8	0.9	0
30	7	0	3	14.0	14.0	13.0	14.0	1.3	0

Table 2. Pheromone trap catches of *Cydia pomonella* in the Elgin and Bellvue orchards on the Elgin and Bellvue Experimental Farms in September 1992. Hourly temperatures between 16:00 and 19:00, daily wind speed and rainfall were obtained from the weather station on the Elgin Experimental Farm.

Date (Sept)	Trap			Temperature (°C)				Daily wind speed (m/s)	Rainfall (mm)
	Elgin 1	Elgin 2	Bellvue	16:00	17:00	18:00	19:00		
1	0	0	0	16.0	15.2	14.4	13.4	1.3	0
2	0	0	0	12.8	12.5	12.1	11.8	2.1	12.4
3	0	0	0	13.0	12.6	11.6	10.5	1.8	3.3
4	0	0	0	14.0	14.2	14.5	13.3	3.2	37.8
5	0	0	0	15.0	14.5	13.8	13.1	2.4	0.4
6	0	0	0	16.0	15.0	14.0	13.0	1.1	0
7	0	0	0	19.4	18.2	15.9	14.0	1.7	0
8	0	0	0	13.6	14.0	13.8	13.3	2.3	0
9	0	0	0	15.6	15.0	14.2	12.6	2.2	0
10	0	0	0	20.4	19.6	17.3	14.5	1.2	2.4
11	0	0	0	20.4	19.6	17.3	14.5	2.0	1.6
12	0	0	0	12.2	12.0	11.7	11.2	1.5	0
13	0	0	0	23.4	23.2	21.3	18.5	1.6	0
14	1	0	2	19.7	17.8	16.4	15.2	2.0	0
15	0	0	0	19.7	18.2	17.0	15.6	1.1	0
16	1	1	0	18.6	17.9	16.8	15.5	1.6	0
17	0	0	1	24.0	23.5	22.1	18.9	1.6	0
18	2	0	1	18.5	17.9	16.8	16.1	3.8	1.1
19	0	0	0	11.0	10.0	10.0	10.0	3.6	7.3
20	0	0	0	14.3	13.4	12.7	11.8	2.3	28.9
21	0	0	0	8.5	9.1	7.9	6.5	2.6	20.9
22	0	0	0	15.0	14.6	13.4	11.3	1.6	0.1
23	0	0	0	16.0	15.0	13.0	12.0	1.5	0
24	1	0	2	16.6	15.5	14.1	12.8	2.3	2.4
25	0	0	0	16.0	15.5	14.4	12.8	1.6	0
26	0	0	0	17.2	16.9	16.1	13.6	1.6	0
27	7	0	21	23.1	22.8	21.6	17.8	1.2	0
28	10	1	5	22.5	21.6	20.7	18.0	1.6	0
29	6	2	8	19.6	20.0	18.8	15.5	1.4	0
30	5	0	2	21.0	20.0	18.0	17.0	1.5	0

Table 3. Pheromone trap catches of *Cydia pomonella* in the Elgin and Bellvue orchards on the Elgin and Bellvue Experimental Farms in September 1993. Hourly temperatures between 16:00 and 19:00, daily wind speed and rainfall obtained from the weather station on the Elgin Experimental Farm.

Date (Sept)	Trap			Temperature (°C)				Daily wind speed (m/s)	Rainfall (mm)
	Elgin 1	Elgin 2	Bellvue	16:00	17:00	18:00	19:00		
1	0	0	0	17.3	15.0	14.2	11.2	1.7	0
2	0	0	0	26.0	20.0	18.1	15.6	1.9	0
3	2	0	0	17.0	17.4	14.9	13.6	2.0	0
4	0	0	0	14.6	14.9	14.5	13.9	3.5	0.6
5	0	0	0	16.5	15.7	14.4	12.5	1.4	0.6
6	0	0	0	23.4	22.1	19.9	17.2	1.5	0
7	4	1	2	22.4	22.3	18.8	15.1	1.1	0
8	0	0	2	26.0	25.0	23.0	21.4	1.0	0
9	1	1	1	27.6	25.8	22.9	21.4	3.5	0
10	3	0	0	14.0	12.2	12.0	11.4	3.9	20.4
11	0	0	0	13.8	13.6	12.6	11.5	1.6	0.8
12	0	0	0	19.4	18.1	15.9	14.5	1.4	0
13	2	0	8	18.7	18.6	16.5	14.2	2.0	0
14	0	0	4	18.9	19.2	18.7	16.7	2.1	0
15	1	0	11	28.6	26.4	24.8	20.9	1.2	0
16	3	1	20	21.3	20.6	19.0	16.6	1.3	0
17	0	0	2	21.4	20.8	18.5	16.1	1.3	0
18	0	0	0	22.2	21.4	19.9	17.6	1.2	0
19	0	0	0	27.4	26.1	24.5	20.5	1.3	0
20	11	1	17	17.1	16.9	15.7	14.6	1.3	2.4
21	0	0	5	12.0	10.0	8.6	8.3	1.3	3.4
22	0	0	0	15.9	15.7	14.8	13.3	1.8	0.2
23	0	0	1	15.7	15.5	14.2	12.9	2.1	0.6
24	0	0	2	19.2	18.3	16.4	14.4	1.4	1.0
25	0	0	0	19.0	19.0	18.0	16.0	1.5	0
26	0	0	0	15.1	14.7	16.6	14.3	1.9	1.6
27	3	2	31	17.1	16.7	16.0	14.5	1.3	0
28	4	0	11	15.7	15.2	14.2	13.2	1.4	0
29	4	0	1	12.8	12.5	11.9	11.9	1.9	0
30	0	0	0	18.3	17.0	15.4	13.8	2.2	0

Table 4. Pheromone trap catches of *Cydia pomonella* in the Elgin and Bellvue orchards on the Elgin and Bellvue Experimental Farms in September 1994. Hourly temperatures between 16:00 and 19:00, average wind speed between 16:00 and 19:00 and rainfall were obtained from the weather station on the Elgin Experimental Farm.

Date (Sept)	Trap			Temperature (°C)				Daily wind speed (m/s)	Rainfall (mm)
	Elgin 1	Elgin 2	Bellvue	16:00	17:00	18:00	19:00		
1	0	0	0	26.1	23.7	21.6	19.3	2.2	0
2	0	0	0	17.2	17.2	15.8	15.0	3.4	0
3	0	0	0	20.6	20.0	18.6	15.9	1.5	0
4	0	0	0	21.0	18.8	17.4	15.3	1.4	0
5	0	0	0	21.5	20.3	19.2	17.9	1.4	0
6	0	0	0	15.0	15.0	15.0	15.0	2.5	0
7	0	0	0	12.3	12.9	12.5	11.8	1.7	0
8	0	0	0	15.7	15.3	13.6	12.4	2.3	0
9	0	0	0	20.7	20.5	19.6	17.8	2.9	0
10	0	0	0	23.1	25.1	25.6	24.2	1.9	0
11	0	0	0	17.4	14.9	14.4	13.7	1.6	3.6
12	0	0	0	18.1	17.2	15.4	14.1	3.1	0
13	0	0	0	14.6	14.0	13.1	11.5	1.9	0
14	0	0	0	19.4	19.4	18.4	15.5	1.4	0
15	2	0	0	23.4	22.7	21.4	18.7	2.0	0
16	0	0	0	16.8	16.0	14.9	13.5	6.1	0
17	0	0	0	10.3	12.6	12.4	12.3	4.4	0
18	0	0	0	15.7	15.6	14.6	13.4	2.2	0
19	0	0	0	20.0	19.0	18.0	16.0	1.4	0
20	0	0	2	20.0	19.1	17.8	15.9	2.0	0
21	0	0	2	23.3	23.2	22.3	20.0	2.1	0
22	2	1	6	16.8	18.0	18.1	16.7	1.4	0
23	3	4	7	17.0	17.0	16.0	16.0	5.3	0
24	0	0	0	20.3	19.3	18.0	16.2	3.9	0
25	0	0	0	24.1	24.0	22.3	19.5	1.8	0
26	6	1	7	21.6	24.0	22.3	19.5	6.5	0
27	0	0	0	14.6	14.0	13.7	13.4	5.7	0
28	1	1	0	13.4	13.4	11.8	11.0	1.8	0
29	1	0	0	18.0	15.8	14.6	13.0	1.9	0
30	2	4	3	17.0	15.0	13.0	13.0	1.6	0

Table 5. Pheromone trap catches of *Cydia pomonella* in the Elgin and Bellvue orchards on the Elgin and Bellvue Experimental Farms in September 1995. Hourly temperatures between 16:00 and 19:00, average wind speed between 16:00 and 19:00 and rainfall were obtained from the weather station on the Elgin Experimental Farm.

Date (Sept)	Trap			Temperature (°C)				Daily wind speed (m/s)	Rainfall (mm)
	Elgin 1	Elgin 2	Bellvue	16:00	17:00	18:00	19:00		
1	0	0	0	15.1	14.6	14.1	13.0	2.2	0
2	0	0	0	12.0	11.5	10.3	10.4	3.4	0
3	0	0	0	13.2	13.0	11.9	11.5	1.5	0
4	0	0	0	16.7	16.4	14.7	13.2	1.4	0
5	0	0	0	20.0	19.3	17.9	15.2	1.4	0
6	0	0	0	19.0	19.0	17.0	15.0	2.5	0
7	0	0	0	19.1	17.6	16.5	14.2	1.7	0
8	0	0	0	16.1	16.1	15.8	14.6	2.3	0
9	0	0	0	14.3	14.1	13.3	12.7	2.9	0
10	0	0	1	18.3	17.3	15.3	13.6	1.9	0
11	0	0	0	15.5	15.2	14.8	14.4	1.6	3.6
12	0	0	0	18.3	18.4	17.2	14.1	3.1	0
13	0	0	0	23.6	22.7	21.5	19.0	1.9	0
14	0	0	0	25.9	25.4	24.0	19.2	1.4	0
15	0	0	0	25.5	24.1	19.2	16.5	2.0	0
16	0	0	0	22.5	21.7	20.0	18.0	6.1	0
17	0	0	0	15.1	12.3	10.8	10.4	4.4	0
18	0	1	0	17.2	16.8	15.8	13.7	2.2	0
19	0	0	0	25.0	25.0	23.0	19.0	1.4	0
20	0	0	0	17.1	15.9	15.7	15.5	2.0	0
21	0	0	1	22.6	21.0	19.9	18.5	2.1	0
22	0	0	0	28.9	28.5	27.4	23.9	1.4	0
23	0	0	0	18.0	15.0	14.0	14.0	5.3	0
24	0	0	0	19.1	18.7	17.3	15.1	3.9	0
25	1	0	2	20.4	18.9	16.4	15.3	1.8	0
26	1	1	0	17.2	16.5	15.6	16.2	6.5	0
27	0	1	2	13.0	13.1	12.3	11.7	5.7	0
28	2	0	0	12.0	11.8	11.7	11.3	1.8	0
29	0	1	0	12.4	12.4	11.2	10.9	1.9	0
30	0	0	0	13.0	13.0	13.0	13.0	1.6	0

Table 6. Pheromone trap catches of *Cydia pomonella* in the Elgin and Bellvue orchards on the Elgin and Bellvue Experimental Farms in October 1996. Hourly temperatures between 16:00 and 19:00, average wind speed between 16:00 and 19:00 and rainfall were obtained from the weather station on the Elgin Experimental Farm.

Date (Oct)	Trap			Temperature (°C)				Daily wind speed (m/s)	Rainfall (mm)
	Elgin 1	Elgin 2	Bellvue	16:00	17:00	18:00	19:00		
1	0	0	0	13.5	12.5	11.8	10.7	2.6	0
2	1	0	1	15.7	14.1	12.8	11.9	1.7	0
3	0	0	0	17.9	16.8	15.5	13.6	1.9	0
4	0	0	0	13.6	13.8	13.3	12.7	2.4	0
5	0	0	0	17.7	16.9	15.7	13.9	2.3	0
6	0	0	0	14.8	15.3	14.5	12.9	2.2	0
7	0	0	0	13.1	12.9	12.4	11.8	1.4	0
8	0	0	0	16.0	15.4	14.6	12.8	2.2	0
9	0	0	0	22.7	23.1	21.0	18.4	1.5	0
10	3	2	5	19.4	18.6	18.2	18.0	4.6	0.2
11	1	2	2	12.8	12.8	12.8	12.8	4.6	3.7
12	0	1	1	15.5	14.5	14.0	13.2	1.5	0
13	2	2	3	18.4	17.5	16.5	15.5	2.5	0
14	2	2	2	14.7	14.0	13.6	12.6	1.3	0
15	3	0	1	19.5	19.1	17.4	15.5	3.3	0
16	1	0	1	25.0	25.4	24.7	21.3	1.7	0
17	0	0	1	27.2	26.3	24.3	21.9	1.6	0
18	6	6	2	25.5	23.3	24.1	24.4	1.6	0
19	6	6	5	14.2	13.8	12.9	12.6	1.7	3.0
20	5	5	5	16.0	15.7	15.1	14.8	1.2	0.2
21	5	5	4	13.2	12.4	12.1	11.2	1.7	0.2
22	6	6	6	17.2	15.6	14.6	14.0	2.2	0
23	2	3	4	17.0	16.6	15.6	15.3	1.3	0.3
24	3	4	5	15.7	15.6	15.3	14.6	1.4	0
25	4	4	6	26.1	26.5	26.1	23.8	1.8	0
26	6	6	7	18.1	17.0	16.0	14.5	1.5	0
27	0	0	0	17.8	17.2	15.9	14.6	1.9	0
28	0	0	0	16.2	15.6	14.7	14.1	1.7	0
29	0	0	0	23.6	22.0	20.5	19.0	2.2	0
30	0	0	2	21.0	20.7	19.6	17.8	1.8	0

Table 7. Pheromone trap catches of *Cydia pomonella* in the Elgin and Bellvue orchards on the Elgin and Bellvue Experimental Farms in September 1997. Hourly temperatures between 16:00 and 19:00, average wind speed between 16:00 and 19:00 and rainfall were obtained from the weather station on the Elgin Experimental Farm.

Date (Sept)	Trap			Temperature (°C)				Daily wind speed (m/s)	Rainfall (mm)
	Elgin 1	Elgin 2	Bellvue	16:00	17:00	18:00	19:00		
1	0	0	0	22.7	22.5	21.6	18.1	2.6	0
2	0	0	0	17.0	16.0	15.7	15.4	1.7	0
3	0	0	0	14.3	14.2	13.8	12.7	1.9	0
4	0	0	0	16.7	16.8	15.0	13.4	2.4	0
5	0	0	0	17.8	17.2	15.6	13.4	2.3	0
6	0	0	0	13.0	14.0	13.0	12.0	2.2	0
7	0	0	0	11.4	10.4	9.6	9.4	1.4	0
8	0	0	0	15.2	15.2	14.3	13.5	2.2	0
9	0	0	0	21.5	21.0	18.3	15.3	1.5	0
10	0	0	0	21.3	21.2	20.3	17.9	4.6	0.2
11	0	0	0	27.4	26.3	25.5	22.5	4.6	3.7
12	0	1	1	32.3	30.6	27.8	24.0	1.5	0
13	2	0	0	32.8	32.3	30.8	25.3	2.5	0
14	4	1	1	31.7	29.9	28.2	25.1	1.3	0
15	0	0	0	17.3	16.2	15.4	14.9	3.3	0
16	0	0	0	14.8	14.4	14.1	13.7	1.7	0
17	0	0	0	21.9	21.4	19.4	17.4	1.6	0
18	8	0	0	27.0	25.9	23.8	21.0	1.6	0
19	0	0	0	16.0	16.0	16.0	14.0	1.7	3.0
20	0	0	0	15.8	15.1	14.4	12.7	1.2	0.2
21	0	0	0	22.5	21.9	20.5	17.7	1.7	0.2
22	0	0	0	25.5	22.6	20.7	19.5	2.2	0
23	1	9	2	20.0	19.0	19.0	18.0	1.3	0.3
24	0	0	0	20.4	19.9	17.4	15.5	1.4	0
25	9	4	2	18.7	18.2	17.6	16.5	1.8	0
26	1	2	2	19.5	18.3	16.8	16.1	1.5	0
27	0	0	0	20.0	19.4	19.2	17.6	1.9	0
28	0	0	0	21.0	20.1	18.0	17.7	1.7	0
29	13	10	2	18.9	19.4	19.3	17.6	2.2	0
30	3	6	2	17.0	17.0	16.0	15.0	1.8	0

Table 8. Pheromone trap catches of *Cydia pomonella* in the Elgin and Bellvue orchards on the Elgin and Bellvue Experimental Farms in September 1998. Hourly temperatures between 16:00 and 19:00, average wind speed between 16:00 and 19:00 and rainfall were obtained from the weather station on the Elgin Experimental Farm.

Date (Sept)	Trap			Temperature (°C)				Daily wind speed (m/s)	Rainfall (mm)
	Elgin 1	Elgin 2	Bellvue	16:00	17:00	18:00	19:00		
1	0	0	0	16.2	17.2	16.1	14.0	1.6	0
2	0	0	0	20.3	19.4	18.2	15.3	1.9	0
3	0	0	0	15.2	14.9	14.6	13.7	2.8	0
4	0	0	0	13.4	12.9	12.4	11.6	2.2	0
5	0	0	0	15.8	15.0	14.0	12.6	1.7	0
6	0	0	0	16.0	15.0	14.0	12.0	2.4	0
7	0	0	0	16.8	15.6	14.0	13.4	2.8	0
8	0	0	0	14.6	14.5	13.4	12.7	2.0	0
9	0	0	0	14.9	14.4	13.5	12.9	1.6	0
10	0	0	0	13.0	13.1	12.6	11.2	2.0	0
11	0	0	0	14.5	13.8	12.9	11.2	2.2	0
12	0	0	0	22.5	21.8	20.2	16.4	1.6	0
13	0	0	0	17.0	16.3	15.0	12.8	2.2	0
14	0	0	0	20.4	19.7	16.7	14.6	1.5	0
15	0	0	0	26.4	26.4	24.8	20.8	1.0	0
16	0	0	0	22.9	23.1	20.0	16.9	1.8	0
17	1	0	1	18.3	17.2	16.0	13.7	1.8	0.2
18	1	0	1	21.2	20.2	18.1	15.8	1.9	0
19	0	0	0	28.0	27.0	26.0	21.0	1.1	0
20	0	0	0	22.7	17.9	16.0	16.4	4.0	0.2
21	1	2	3	20.0	19.9	18.3	15.5	3.2	0
22	1	0	2	12.9	13.1	13.3	13.4	6.2	1.1
23	1	0	1	14.0	14.0	14.0	14.0	3.8	0
24	0	0	0	8.8	9.1	9.2	8.6	3.3	0.1
25	0	0	0	13.4	13.1	12.4	10.5	2.6	0
26	0	0	0	14.1	13.2	11.9	10.6	3.5	0
27	0	0	0	11.0	11.0	10.7	8.5	1.9	0
28	0	0	0	13.9	13.1	12.5	10.8	2.1	0
29	0	0	0	19.6	19.1	17.8	15.7	2.1	0
30	3	0	0	17.0	16.0	15.0	14.0	3.1	0

Table 9. Accumulated degree-days from three biofix dates to first egg hatch of *Cydia pomonella* eggs of the 1st generation in the Elgin orchard, Elgin Experimental Farm, Grabouw, Western Cape from 1991 to 1996 and 1998. Degree-days were calculated from hourly temperatures. Temperature at 18:00 given in parentheses.

Year	Biofix			First egg hatch	Degree-days		
	1st trap catch	2nd trap catch	First evening temp. at 18:00 at or above 17°C after 1st trap catch		1st trap catch	2nd trap catch	First evening temp. at 18:00 at or above 17°C after 1st trap catch
1991	19 Sept	21 Sep	22 Sep (18.6°C)	24 Oct	142.6	138.9	130.9
1992	14 Sep	16 Sep	15 Sep (17.0°C)	19 Oct	152.5	141.0	148.2
1993	3 Sep	7 Sep	6 Sep (19.9 °C)	12 Oct	179.0	164.0	165.5
1994	15 Sept	22 Sep	19 Sep (18.0°C)	18 Oct	170.8	144.1	157.5
1995	25 Sep	26 Sep	1 Oct (17.0°C)	31 Oct	130.7	129.3	113.3
1996	2 Oct	10 Oct	9 Oct (21.0°C)	7 Nov	167.9	142.4	146.5
1998	17 Sept	18 Sep	18 Sep (26.0°C)	20 Oct	140.8	134.7	134.7

Table 10. Accumulated degree-days from three biofix dates to first egg hatch of *Cydia pomonella* eggs of the 1st generation in the Bellvue orchard, Bellvue Experimental Farm, Grabouw, Western Cape from 1992 to 1998. Degree-days were compared when calculated from hourly temperatures. Temperature at 18:00 given in parentheses.

Year	Biofix			First egg hatch	Degree-days		
	1st trap catch	2nd trap catch	First evening temp. at 18:00 at or above 17°C after 1st trap catch		1st trap catch	2nd trap catch	First evening temp. at 18:00 at or above 17°C after 1st trap catch
1992	14 Sep	16 Sep	15 Sep (17.0°C)	14 Oct	139.2	127.7	133.5
1993	7 Sep	8 Sep	6 Sep (19.9 °C)	12 Oct	164.0	157.5	165.5
1994	20 Sep	21 Sep	21 Sep (22.3°C)	16 Oct	140.8	135.5	135.5
1995	11 Sep	21 Sep	12 Sep (17.2)	27 Oct	182.2	132.7	174.0
1996	2 Oct	10 Oct	9 Oct (21.0°C)	3 Nov	153.4	127.9	132.0
1997	12 Sep	14 Sep	13 Sep (30.8)	8 Oct	156.6	136.4	147.2
1998	17 Sep	18 Sep	18 Sep (18.1°C)	20 Oct	140.8	134.7	134.7

Table 11. Results of the 2 x 3 factorial analysis of variance with seven replications (years) in a complete randomized design to compare differences between the Elgin and Bellvue farms and three methods (biofixes) for timing the first codling moth spray to coincide with first egg hatch (timing based on number of degree-days between biofix and egg hatch).

Source	DF	MS	P-level
Farm	1	13.1488	0.8131
Method	2	850.8671	0.0354
Farm x Method	2	82.1017	0.7041
Error	36	231.7662	
Total	41		

Table 12. Accuracy of the full-bloom date versus the codling moth phenology model for timing the commencement of the 1st generation spray program on Golden Delicious (GD) and Granny Smith (GS) trees in the Elgin orchard, Elgin Experimental Farm, Grabouw, between 1991 and 1996 and 1998.

Year	Biofix			First egg hatch	Full bloom date		Model timing date			Accuracy of spray based on:				
										Full bloom		Model		
	1st	2nd	3rd		GD	GS	1st	2nd	3rd	GD	GS	1st	2nd	3rd
1991	19 Sep	21 Sep	22 Sep	24 Oct	29 Oct	21 Oct	23 Oct	23 Oct	24 Oct	+5	+3	+1	+1	0
1992	14 Sep	16 Sep	15 Sep	19 Oct	24 Oct	16 Oct	13 Oct	18 Oct	16 Oct	-5	+3	+6	+1	+3
1993	3 Sep	7 Sep	6 Sep	12 Oct	19 Oct	11 Oct	5 Oct	7 Oct	7 Oct	-7	+1	+7	+5	+5
1994	15 Sep	22 Sep	19 Sep	18 Oct	19 Oct	9 Oct	14 Oct	16 Oct	15 Oct	-1	+9	+4	+2	+3
1995	25 Sep	26 Sep	1 Oct	31 Oct	23 Oct	16 Oct	31 Oct	31 Oct	3 Nov	+8	+15	0	0	-3
1996	2 Oct	10 Oct	9 Oct	6 Nov	31 Oct	26 Oct	31 Oct	6 Nov	5 Nov	+7	+12	+6	0	+2
1998	17 Sep	18 Sep	18 Sep	20 Oct	20 Oct	13 Oct	19 Oct	20 Oct	20 Oct	0	+7	+1	0	0

Table 13. Accuracy of the full-bloom date versus the codling moth phenology model for timing the commencement of the 1st generation spray program on Golden Delicious (GD) and Granny Smith (GS) trees in the Bellvue orchard, Bellvue Experimental Farm, Grabouw, between 1992 and 1998.

Year	Biofix			First egg hatch	Full bloom date		Model timing date			Accuracy of model timing based on:				
										Full bloom		model		
	1st	2nd	3rd		GD	GS	1st	2nd	3rd	GD	GS	1st	2nd	3rd
1992	14 Sep	16 Sep	15 Sep	14 Oct	18 Oct	16 Oct	15 Oct	19 Oct	19 Oct	-4	-2	+1	-4	-2
1993	7 Sep	8 Sep	6 Sep	12 Oct	19 Oct	9 Oct	7 Oct	8 Oct	7 Oct	-7	+3	+5	+4	+5
1994	20 Sep	21 Sep	21 Sep	16 Oct	19 Oct	12 Oct	15 Oct	16 Oct	16 Oct	-3	+4	+1	0	0
1995	11 Sep	21 Sep	12 Sep	27 Oct	23 Oct	16 Oct	15 Oct	28 Oct	16 Oct	+4	+11	+12	-1	+11
1996	2 Oct	10 Oct	9 Oct	3 Nov	31 Oct	26 Oct	31 Oct	6 Nov	5 Nov	+3	+8	+3	-3	-2
1997	12 Sep	14 Sep	13 Sep	8 Oct	13 Oct	12 Oct	3 Oct	8 Oct	4 Oct	-5	-4	+5	0	+4
1998	17 Sep	18 Sep	18 Sep	20 Oct	20 Oct	13 Oct	19 Oct	21 Oct	21 Oct	0	+7	+1	0	0

Table 14. Percentage egg hatch, infertility and mortality of the first eggs laid by *Cydia pomonella* moths of the spring generation on Granny Smith trees in the Elgin and Bellvue orchards from 1991 to 1996 and 1998. Dislodgment of eggs attributed to rain, wind and predation.

Year	Orchard	Number of eggs	% hatch	% Infertility	% Mortality due to:		
					Desiccation	Parasitism	Dislodgement
1991	Elgin	104	53.8	15.4	13.5	0	17.3
	Bellvue	-	-	-	-	-	-
1992	Elgin	33	18.2	0	57.6	0	24.2
	Bellvue	100	50.5	14.9	17.8	1.0	15.8`
1993	Elgin	104	51.0	11.5	26.9	1.0	9.6
	Bellvue	126	45.2	9.5	39.7	0.8	4.8
1994	Elgin	50	66	4	12	1.0	18
	Bellvue	122	50	21.3	14.8	0.8	13.1
1995	Elgin	50	74	8	8	0	10
	Bellvue	50	56	2	8	0	34
1996	Elgin	63	77.8	4.8	6.3	0	11.1
	Bellvue	100	93.1	2.9	2	0	2
1997	Elgin	20	15	20	60	0	5
	Bellvue	50	28	4	56	0	12

Table 15. Percentage egg hatch of the first eggs laid *by Cydia pomonella* of the spring generation on Granny Smith trees in the Elgin orchard, Elgin Experimental Farm, Grabouw, Western Cape from 1991 to 1996 and in 1998. Accumulative egg hatch was recorded at irregular intervals following a 14-day period after first egg hatch.

Year	No of eggs	Biofix	Date of first egg hatch (% egg hatch)	Accumulative egg hatch following first egg hatch (%)													
				Day													
				1	2	3	4	5	6	7	8	9	10	11	12	13	14
1991	104	21 Sept	24 Oct (1.0)	1.0	-	-	10.6	-	15.4	-	25.0	-	-	53.8	-	-	-
1992	33	16 Sept	19 Oct (3.0)	-	3.0	-	-	3.0	-	3.0	-	-	18.2	-	-	-	-
1993	104	7 Sept	12 Oct (1.9)	3.8	-	4.8	-	-	5.8	-	10.6	-	-	-	-	45.2	-
1994	50	22 Sept	18 Oct (2.0)	2.0	-	14.0	-	-	38.0	-	62.0	-	66.0	-	-	-	-
1995	50	26 Sept	31 Oct (2.0)	-	-	36.0	-	-	70.0	74.0	-	-	-	-	-	-	-
1996	63	10 Oct	6 Nov (4.8)	11.0	-	-	33.3	-	55.6	-	-	-	65.0	-	-	-	77.8
1998	20	18 Sept	20 Oct (5.0)	10.0	-	10.0	-	-	-	15.0	-	-	15.0	-	-	-	-

Table 16. Percentage egg hatch of the first eggs laid by *Cydia pomonella* of the spring fight on Granny Smith trees in the Bellvue orchard on the Bellvue Experimental Farm, from 1992 to 1998. Accumulative egg hatch was recorded at irregular intervals following a 14-day period after first egg hatch.

Year	Number of eggs	Biofix	First egg hatch (% egg hatch)	Accumulative egg hatch following first egg hatch (%)													
				Day													
				1	2	3	4	5	6	7	8	9	10	11	12	13	14
1992	100	16 Sept	14 Oct (6.0)	6.0	-	7.0	-	-	11.0	-	-	-	-	-	23.0	34.0	35.0
1993	126	8 Sept	12 Oct (0.8)	3.1	-	12.0	-	-	23.8	-	37.6	-	-	-	-	45.2	-
1994	122	21 Sept	16 Oct (5.7)	31.1	42.2	-	-	45.9	-	-	49.2	-	50.0	-	-	-	-
1995	50	21 Sept	27 Oct (2.0)	4.0	8.0	36.0	40.0	-	-	52.0	-	-	56.0	56.0	-	-	-
1996	102	10 Oct	3 Nov (5.9)	12.7	27.5	-	-	59.8	-	-	92.2	-	93.1	-	-	-	-
1997	36	14 Sept	8 Oct (2.8)	2.7	5.6	-	-	-	5.6	-	16.2	-	-	-	-	-	-
1998	50	18 Sept	20 Oct (4.0)	4.0	-	14.0	-	-	-	20.0	-	-	28.0	-	-	-	28.0

Table 17. Biofix for the first and second moth flights of *Cydia pomonella*, accumulative degree-days to 50 % egg emergence and 50 % oviposition of the first flight, appearance of the second moth flight and predicted moth flight for the third generation.

Year	First moth flight					Second moth flight		Predicted third moth flight**
	Biofix*	50 % emergence	Degree-days	50 % oviposition	Degree-days	Biofix *	Degree-days from first flight	
1983/84	5 Sep	26 Oct	188.7	-	-	8 Dec	492.1	29 Jan
1984/85	22 Aug	11 Oct	146.7	-	-	5 Dec	506.5	30 Jan
1985/86	4 Sep	14 Oct	163.7	9 Nov	322.7	28 Nov	531.2	22 Jan
1986/87	22 Sep	22 Oct	121.1	19 Nov	252.3	15 Dec	488.6	14 Feb
1897/88	14 Sep	30 Oct	199.4	4 Nov	253.2	10 Dec	488.8	8 Feb
1988/89	19 Sep	3 Nov	173.2	22 Nov	331.6	18 Dec	522.1	7 Feb
1989/90	11 Sep	31 Oct	173.3	-	-	18 Dec	527.7	10 Feb
Mean ± SE			166.6 ± 9.91				508.1 ± 7.11	

* Based on the beginning of the week in which more than one male was first recorded

** Based on a development time of 508 degree-days for a generation

Table 18. Log-probit equations for the emergence and oviposition for the spring flight between the 1985/86 and 1988/89 seasons.

Year	Emergence	50 % emergence (°D)	Oviposition	50 % Oviposition (°D)
1985	$y^a = -15.818 + 7.401 \log x^b$ $r^2 = 0.98$	137.1	$y = -29.739 + 11.656 \log x$ $r^2 = 0.97$	356.0
1986	$y = -24.884 + 11.121 \log x$ $r^2 = 0.93$	172.8	$y = -23.662 + 9.600 \log x$ $r^2 = 0.94$	291.7
1987	$y = -25.630 + 10.820 \log x$ $r^2 = 0.94$	233.7	$y = -22.635 + 9.049 \log x$ $r^2 = 0.86$	317.2
1988	$y = -24.357 + 10.439 \log x$ $r^2 = 0.93$	215.4	$y = -25.781 + 10.098 \log x$ $r^2 = 0.86$	357.3
Mean		189.8		330.0

[a] : y expressed in probits
[b] : x degree-days after first moth catch

Table 19. Comparison between full-bloom date versus codling moth phenology model for timing the commencement of the 1st generation spray program on Forelle pears in cold and warm pome fruit production areas in the Western Cape from 1994 to 1996.

Cold pome fruit area: Koue Bokkeveld				
Year	Biofix	Full bloom timing	Model timing	Days between full bloom and model timing spray
1994	22 Aug	5 Sep	6 Oct	+ 31
1995	11 Sep	19 Sep	30 Oct	+ 42
1996	7 Oct	7 Sep	14 Nov	+ 38
Warm pome fruit area: Warm Bokkeveld				
1994	22 Aug	15 Sep	23 Sep	+ 8
1995	11 Sep	17 Sep	13 Oct	+ 26
1996	10 Oct	30 Sep	7 Nov	+ 38

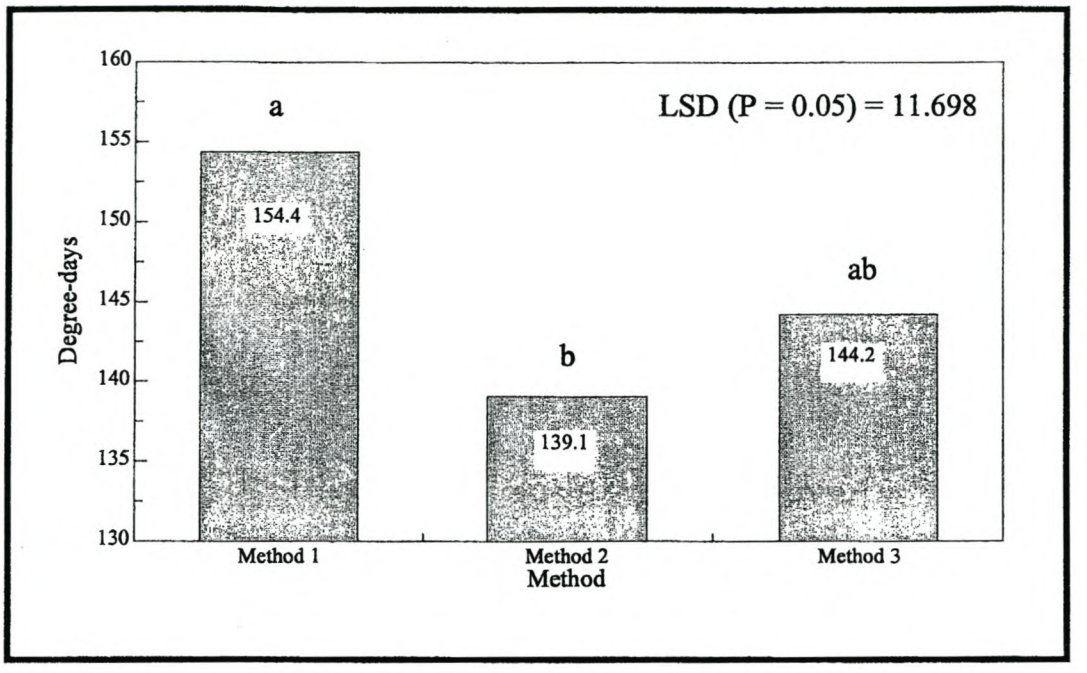


Fig. 1. Mean accumulative degree-days between biofix and first egg hatch for methods 1,2 and 3. (Method 1= first trap catch; Method 2 = second trap catch; Method 3 = first evening at 17°C or more at 18:00 after first trap catch.

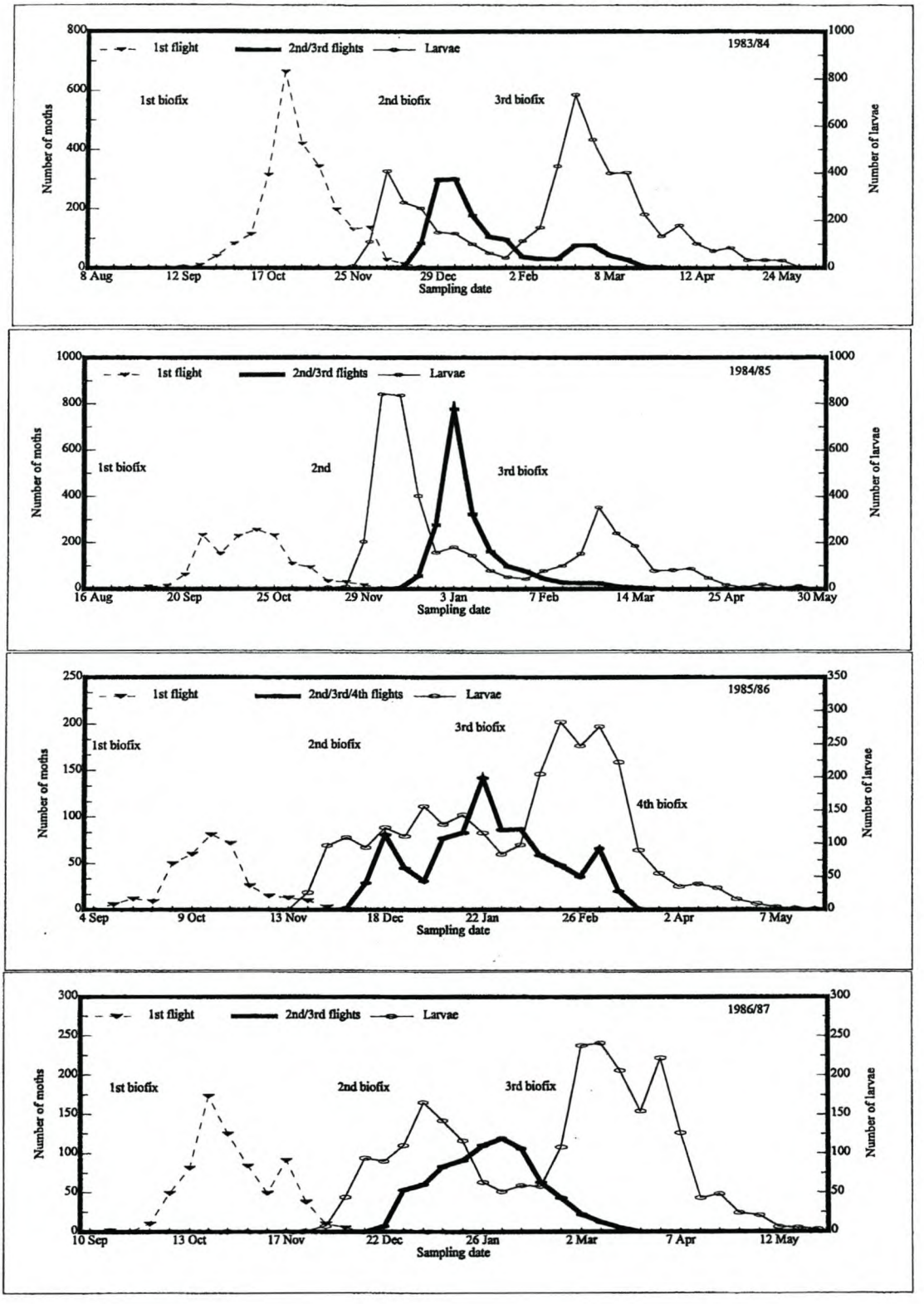


Fig. 2. Seasonal occurrence of *Cydia pomonella* between 1983/84 and 1986/87 seasons as shown by the emergence of moths of the 1st flight from diapausing larvae collected weekly in corrugated cardboard bands the previous season; mature larvae leaving the fruit and collected in cardboard bands at weekly intervals; weekly record of moths of the 2nd and 3rd flights from transforming larvae collected in cardboard bands housed in containers suspended from branches in the orchard.

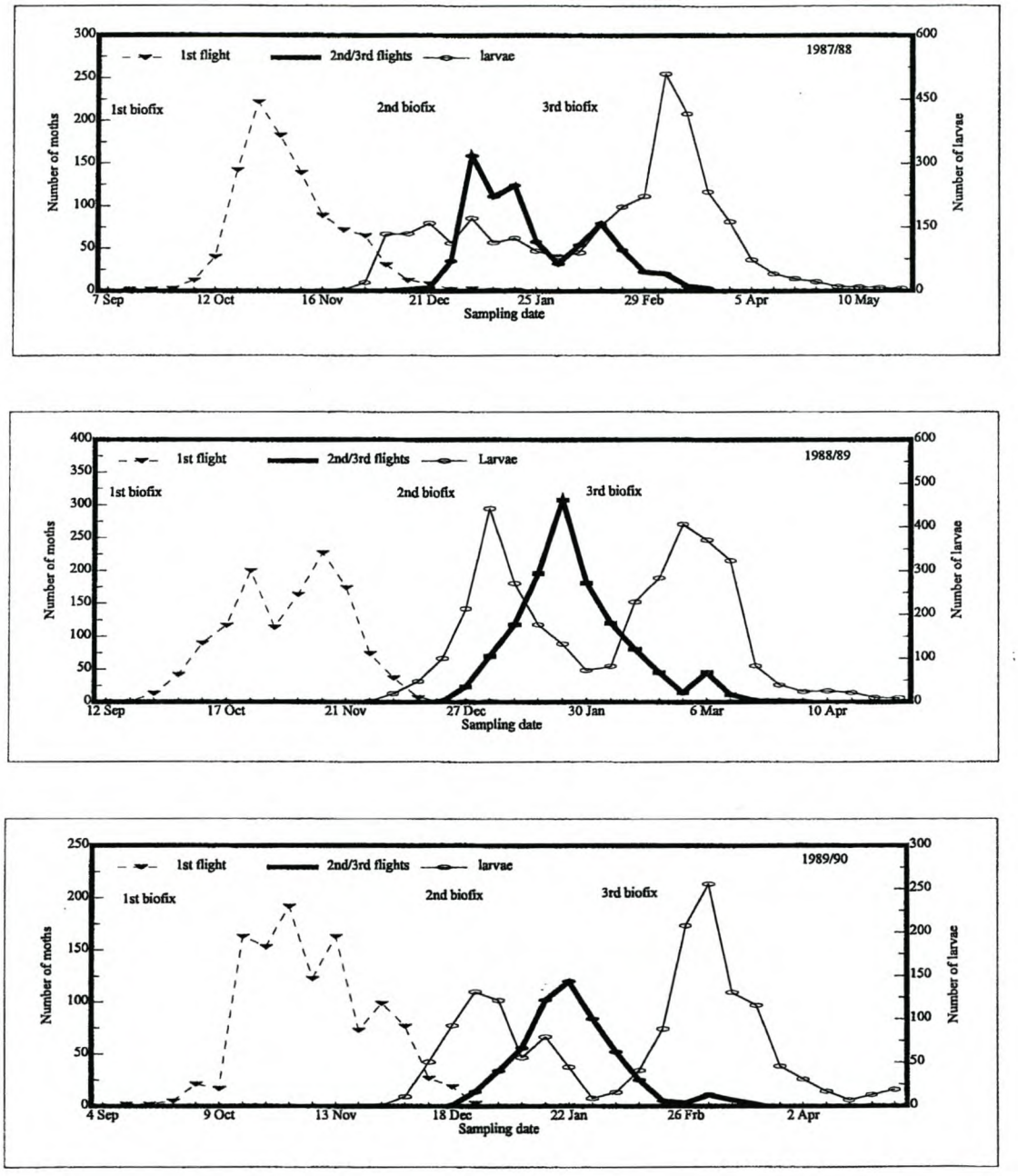
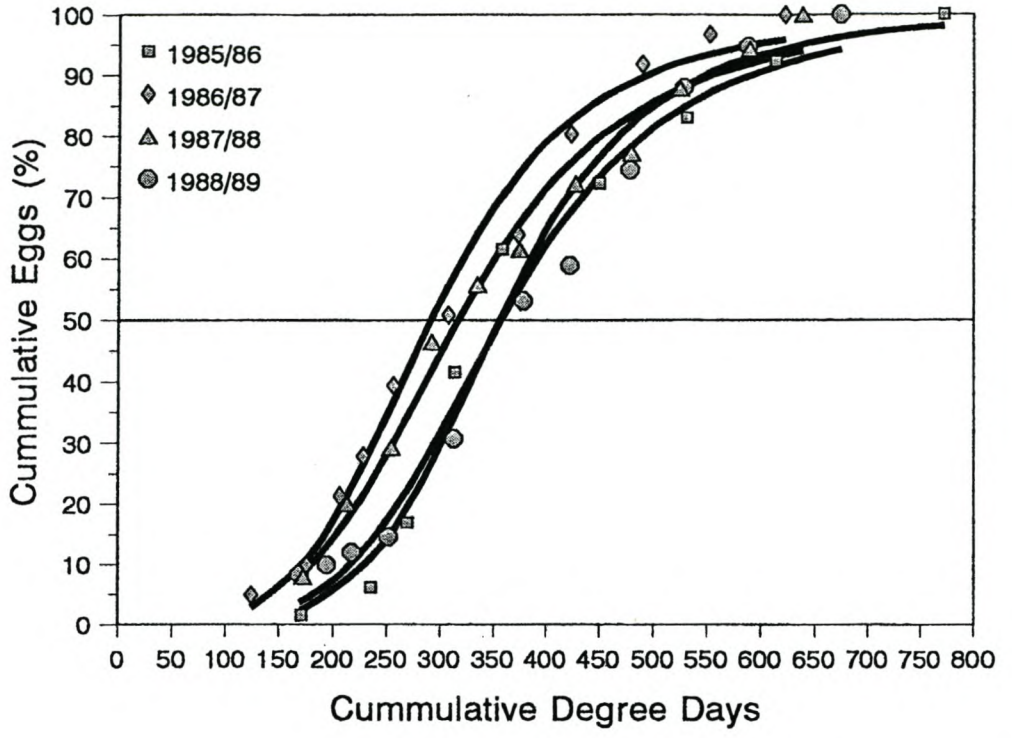


Fig. 3. Seasonal occurrence of *Cydia pomonella* between 1987/88 and 1989/90 as shown by the emergence of moths of the 1st flight from diapausing larvae collected weekly in corrugated cardboard bands the previous season; mature larvae leaving the fruit and collected in cardboard bands at weekly intervals; weekly record of moths of the 2nd and 3rd flights from transforming larvae collected in cardboard bands housed in containers suspended from branches in the orchard.



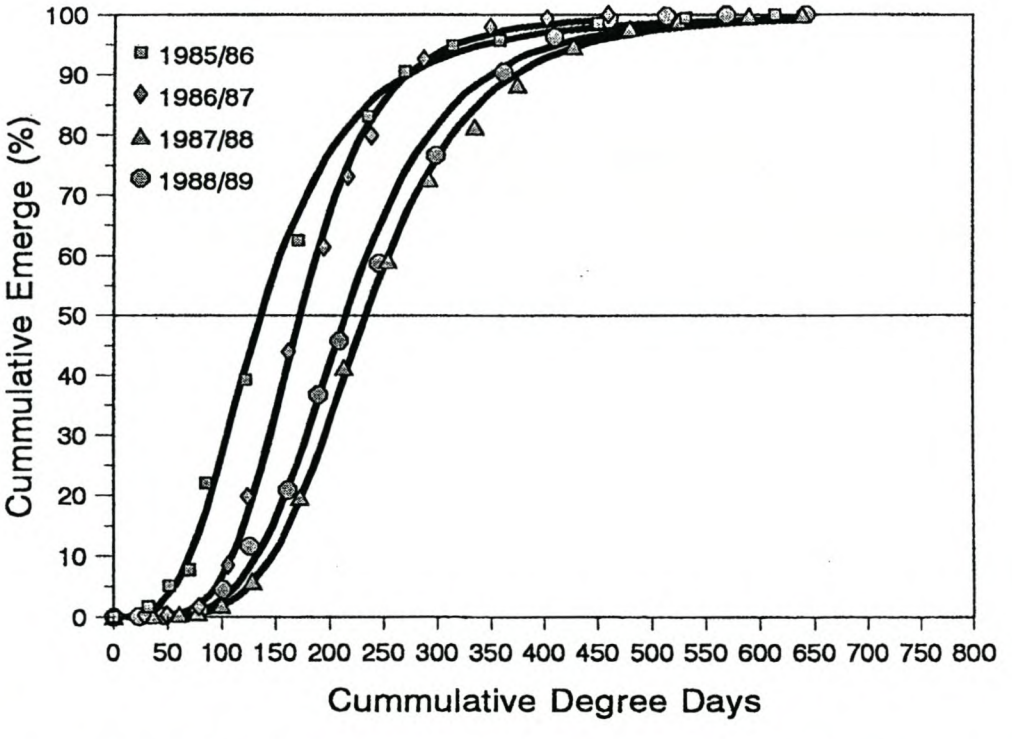


Fig. 4. Percentage cumulative emergence and oviposition curves for the spring generations between 1985/86 and 1988/89 seasons.

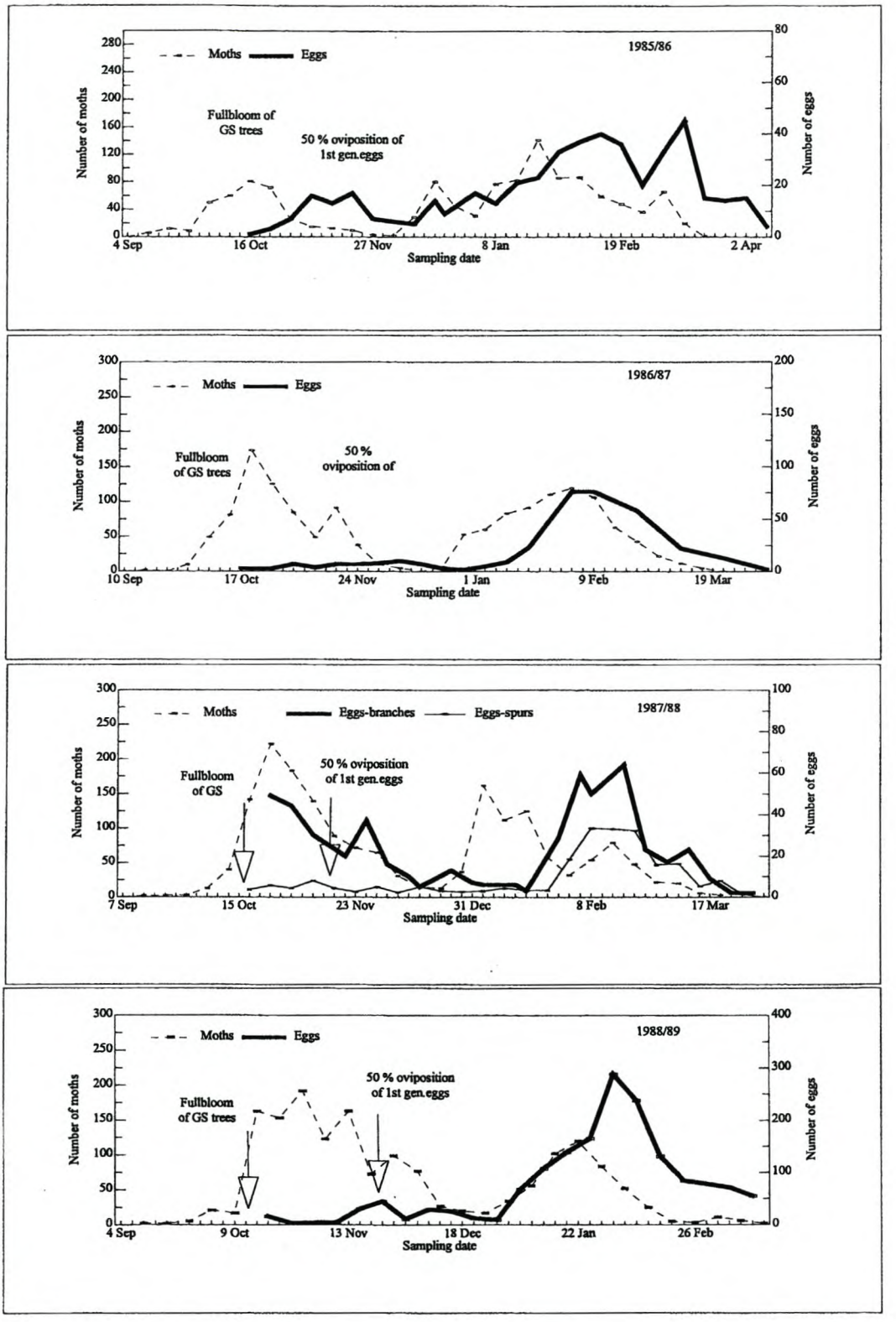


Fig. 5. Emergence and oviposition on fruit spurs (1985/86-1987/88) and branches (1987/88 - 1988/89) of *Cydia pomonella* recorded weekly in an unsprayed apple orchard between 1985/86 and 1988/89 seasons.

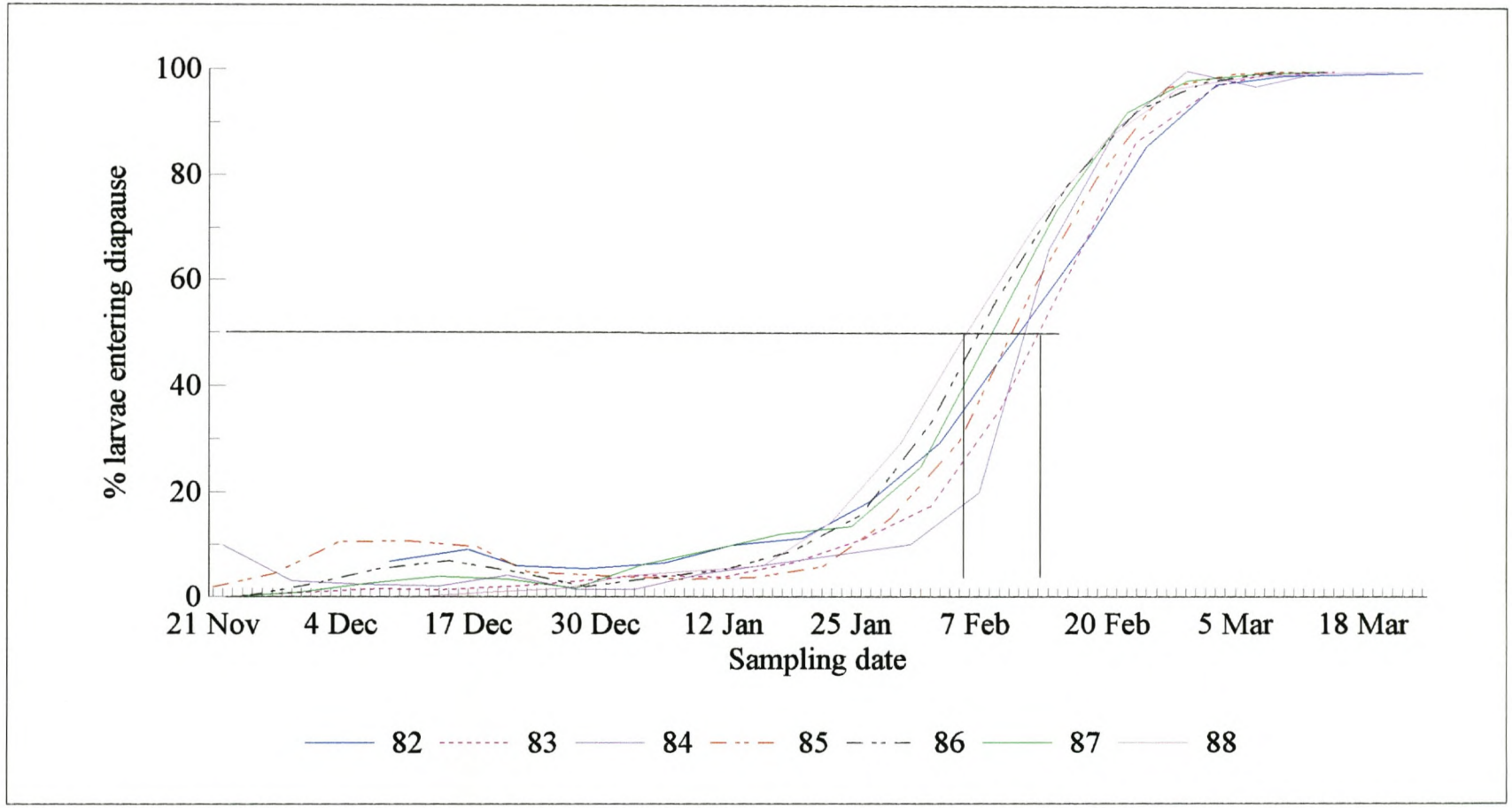


Fig. 6. Percentage diapausing larvae collected in corrugated cardboard bands placed around the trunk and branches of Granny Smith trees in an unsprayed apple orchard on the Elgin Experiment Farm for each year between 1982/83 and 1987/88.

6. GENERAL CONCLUSION

Effective management of codling moth can be improved by a thorough understanding of its bilogy, particularly its oviposition behaviour, and the management of the habitat of codling moth in such a manner that it is less favourable to its development without sacrificing fruit production. It is important to use sampling methods that provide a more complete account of codling moth oviposition in order to achieve better control of this pest.

The movement toward the use of less disruptive and safer insecticides has renewed interest in the insect growth regulators (IGRs). These chemicals interfere with insect growth and development. There are three groups of the IGRs that have been researched for insect pest and mite control since diflubenzuron was first discovered. They are the chitin-synthesis inhibitors, the juvenile hormone mimics and the ecdysone agonists. Most of these products have ovicidal activity, particularly against eggs laid on a treated surface, or they have both ovicidal and larvicidal activity. Early in the season, codling moth oviposition is concentrated in the lower half of the tree where blossoming starts. Therefore, it is important to ensure that this area of the tree receives effective coverage. Other further factors that may affect the performance of the IGRs are the physical properties of the oviposition surface. Although more eggs are laid on the upper surface of Granny Smith (GS)and Topred (TR) leaves, a large number are also deposited on the more pubescent lower leaf surface of these cultivars. Even though the lower surface of Golden Delicious leaves have a low trichome density in comparison to the lower leaf surface of GS and TR, most of the eggs were also laid on this surface. During oviposition the female moth rubs her ovipositor lobes over the leaf surface. This rubbing action may create an 'opening' in the mat of fine intertwining trichomes. The egg is then deposited mainly on the epidermis of the leaf. The trichomes form a mat that covers the epidermis of the leaf and may affect the amount of insecticide that reaches the leaf surface to which the greater part of the egg is attached. Therefore, this 'hairy mat' of trichomes must also be penetrated. It may be advantageous to use surfactants on cultivars with densely pubescent leaves to provide better coverage and spray penetration of the 'hairy mat'. This would be particularly pertinent when sprays are applied at low volume. Such sprays should not be applied during the heat of the day or under windy conditions.

The fruit spur is the target for oviposition and proportionally more eggs are laid on spurs with multiple fruit. Consequently the incidence of apple damage and larval survival on multiple fruit spurs will be higher. In addition, on multiple fruit spurs the shielding effect created by apples during spraying will

adversely affect cover, resulting in reduced control by the IGRs. Furthermore, since penetration of the hard skin of the apple requires considerable effort, larvae seek the easiest and most protected position to penetrate the apple. This is often in the crevice between touching apples where maximum leverage can be obtained. It has also been shown that most of the eggs laid on the fruit are deposited in the fovea and shoulder area. Effective insecticide cover of these areas will be more difficult on spurs with multiple fruits, as a result of the shielding effect. Therefore, it would appear that if ovicidal insecticides are used, fruit-bearing spurs should be limited to a single apple. It is important that before an insecticide is applied, particularly one possessing ovicidal properties, a thorough understanding of the oviposition behaviour and physical nature of the surface to which the chemical is to be applied is required.

The prediction of phenological events of orchard pests has become an increasingly important part of pest management. The biological parameters needed for the prediction of phenological events are threshold temperatures and development rates of the embryonic and immature stages of codling moth expressed as degree-days. The average number of degree days to complete a life cycle under variable temperatures was similar to that obtained under constant temperature conditions. Although the greatest variation occurred during the incubation period at average ambient temperatures below 17°C, the similarity in degree-days requirements under constant and variable temperature conditions indicates that the estimate of the lower threshold temperatures can be incorporated into a phenology model. Current control recommendations for codling moth on pome fruit are the commencement of the spray programme at full-bloom. However, in the cooler pome fruit producing areas there can be a two to four week period between full-bloom and egg hatch. A degree-day prediction for first egg hatch, using pheromone traps to accurately pin-point the commencement of the first moth flight, will improve the timing of the first cover spray and reduce the number of sprays applied.

In commercial orchards larval infestation of fruit can occur as a result of a control failure either due to the mistiming of a spray applications, inadequate spray coverage or development of resistance. The similarity of the mean head capsule width, with minimal overlap of instars, of larvae removed from fruit of different maturity and at different times of the year suggests that the head capsule width can be used to accurately identify larval instars. In addition the linear relationship between the larval development rate and temperature, the similarity in degree-days for each instar, and the similarity in instar composition and degree-days obtained under fluctuating temperatures, suggest that the head capsule width can be used to approximate the age of larvae and time of fruit infestation in the case of

control failures. Head capsule width together with temperature data as well as other climatic information, such as rain or favourable oviposition periods, can assist producers in identifying the time of fruit infestation and possible causes of control failures.

An obvious limitation of caged oviposition studies is that the moths are restricted to confined spaces. This may have a negative effect on longevity and oviposition, particularly under summer conditions. Furthermore, there is the exclusion of extrinsic mortality factors. However, despite the limitations, these studies have provided useful information that permits comparison to similar studies by researchers in other apple producing areas of the world. These studies also provides a guide as to the biotic potential of codling moth and what can be expected under field conditions. This information can be used to evaluate the present control strategies against codling moth, particularly with respect to monitoring, treatment threshold and the timing of sprays.

The short interval between peak oviposition and 80% of the total eggs laid by summer moths at fluctuating temperatures, a period of less than four days, raises doubts concerning the present recommendations on the use of codling moth sex pheromone traps for determining the need and the timing of insecticide sprays in pome fruit orchards in South Africa. The present recommendations are that an activity level of two or more moths for two or more consecutive weeks represents a critical level. If this threshold is exceeded a spray should be applied. The observation that 50% of the eggs can be laid in approximately three days, and egg hatch occurs within six to seven days at summer temperatures, suggests that the interval between trap inspections should occur more frequently than the present weekly interval. This will be especially important if the moths emerge and are trapped in the beginning of the week. Most of the eggs laid in the first week would have hatched and the larvae penetrated the fruit by the end of the second week. If the spray is delayed by unfavourable weather conditions the situation may arise were larvae of the second week emerge and enter the fruit before a treatment is applied. More frequent monitoring could be confined to critical times, such as peak moth activity, or the period of oviposition that gives rise to the moths of the third generation. Oviposition studies have also shown that fecundity of summer moths is significantly higher than spring moths and this should be taken into account in the control strategy against codling moth during the summer months. The results also indicated that periods of unfavourable weather can be followed by optimum oviposition conditions resulting in high numbers of eggs being produced in a period of 1 to 3 days. More frequent monitoring would pin-point these periods and lead to sprays being applied in a timely fashion.

The detailed information on development rates of the various stages, oviposition, longevity, mating and mortality of the various life stages of codling moth would hopefully lead to a better understanding of the pest, the necessity for refinements of the currently used management actions and ultimately improved control.

There is an increasingly greater demand globally to become less dependant on insecticides for codling moth control, in particular organophosphate insecticides. The success achieved at controlling codling moth with mating disruption (MD) has shown that pome fruit prodution can become largely independent of organophosphate insecticides. Mating disruption can be compared to DDT that heralded a revolution in the economic control of insect pests. Mating disruption has heralded a revolution in the resistance management of codling moth. In many pome fruit production areas of the world as well as in South Africa MD has given growers a new tool to deal effectively with resistance and cross-resistance to many of the insecticides used to control codling moth. This new control method has also satisfied consumer demands for a reduction in the use of insecticides. A reduction of codling moth population levels through pheromone-based management has not only reduced the use of organophosphates but created a more favourable climate for the use of biopesticides and environmentally acceptable insecticides that are considered to be less effective than the organophosphates at higher population levels. The monitoring of codling moth populations in MD orchards, where populations have been reduced to very low levels, is always going to present a problem. The difficulty of monitoring codling moth in MD orchards with the traditional method of pheromone traps will require the implementation of more detailed fruit sampling during the season and at harvest. Probably the greatest danger to the successful implementation of a MD programme is insufficient and inadequate management inputs and lack of technical support.

It has been shown, however that MD can not be considered a stand alone approach, particularly under hot, dry conditions which favour codling moth. Under such conditions insecticide inputs or additional control methods are required from time to time. If improved control of codling moth can be achieved with light summer oils, without increasing the risk of phytotoxicity, they could become a very valuable additional control option, particularly in combination with MD. If one or more insecticide sprays could be replaced with light summer oil sprays the danger of resistance and dependance on insecticides would be further reduced, particularly where codling moth is controlled with MD and one to three insecticide sprays. The newer summer oils with improved emulsifiers would appear to have improved efficacy and early trials indicate that these products are comparable to azinphos-methyl in

efficacy when applied at high volume. There is also the possibility of combining oils with biopesticides, such as the codling moth granulosis virus, for improved efficacy.

Although non-insecticidal methods of control will become increasingly important in the future there will always be orchards that for various reasons are not be suitable for codling moth control with methods such as MD. It is therefore essential to use the insecticides presently available to growers in a manner that ensures a delay or reduction in the development of resistance. This study has shown that alternation of insecticides across generations can provide acceptable control of codling moth even when products are used that are not particularly effective when used on their own.

Codling moth management is greatly improved with the use of a phenology model in conjunction with pheromone trap data. The phenology model provides a more accurate forecast of the commencement of the codling moth spray programme than tree phenology. This can lead to a saving of sprays, particularly in the cooler pome fruit production areas, or during a cool spring and early summer periods. The model also provides a tool for determining key periods of activity for this pest, such as peak oviposition and egg hatch, periods during which the spray interval should not be exceeded and attention should be given to achieving optimum spray cover. By accurately determining the commencement of the second flight an indication can be obtained of the potential of a small or larger third flight or even a fourth flight.

Pome fruit production no longer revolves solely around product quality and markets but also chemical residues, pathogens, water quality, orchard environment safety, worker safety and social development. As a result of globalization quarantine regulations have become stricter and more internationally driven to reduce the risks of introducing pests into new areas of the world. Greater accountability has been passed on to producers and industry to implement guidelines and structures that not only monitor fruit safety but ensure a healthy and sustainable orchard environment. These are all interwoven and now form part of integrated pome fruit production. While this approach has positive ecological and social attributes it may negatively affect the competitive edge of pome fruit production and economic viability of apple production.

Codling moth is the key pest in pome fruit orchards in South Africa. Insecticides remain the primary means of control with up to 11 insecticide sprays being applied to control this pest. These insecticide sprays impact not only on the target pest but other primary and secondary insect pests, their natural

enemies and the environment. As codling moth sprays comprise the bulk of insecticides sprays applied to apple orchards any movement away from a control programme based primarily on insecticides to one based on non-insecticidal methods, will help to reduce our reliance on insecticides and improve our competitive edge and international acceptance as a region in the forefront of applied integrated pest management.

APPENDIX 1

Cydia pomonella 10 mg trap counts during the 1995/96 season in G70 and G5 on Oak Valley Estates, Elgin.

Date	G70						G5				
	Trap number						Trap number				
	1	2	3	4	5	6	1	2	3	4	5
18	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0
3 October	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	5	3	0	0	0	0	0
23	3	0	1	1	2	7	1	1	1	2	2
31	1	2	1	0	8	16	1	2	0	1	0
7	19	4	4	5	0	1	1	6	0	3	3
14	2	1	0	0	12	6	0	3	0	0	1
21	7	1	4	3	0	1	1	17	4	12	2
28	5	0	0	0	4	2	0	9	1	0	0
5	13	11	8	3	0	2	0	29	4	8	4
12	6	7	0	0	7	15	0	10	2	0	1
20	32	1	3	2	0	0	3	10	1	0	0
27	1	0	2	1	0	0	0	0	0	0	0
3 January	1	0	0	0	0	0	1	6	3	2	4
9	0	0	0	0	0	0	0	0	0	0	0
16	1	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	1	0	0	0
6 February	0	0	0	0	0	0	0	1	0	0	0
14	3	0	0	2	4	1	0	2	0	0	0
20	2	0	0	1	0	1	0	1	0	0	0
27	1	0	0	0	1	1	0	0	0	2	0
5 March	1	0	0	1	4	0	1	9	0	0	0
12	0	1	0	7	0	1	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	1	0
2 April	1	2	1	0	1	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	1	0

APPENDIX 2

Cydia pomonella 10 mg trap catches during the 1995/96 season in G4B, G4T and G61on Oak Valley Estates, Elgin.

Date	G4B				G4T				G61		
	Trap number				Trap number				Trap number		
	1	2	3	4	1	2	3	4	1	2	3
18	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0
3 October	0	0	0	0	0	0	0	0	0	0	0
10	0	1	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	5	0	0	0	0
23	1	0	0	3	0	5	1	2	0	0	0
31	0	0	1	0	0	0	0	1	0	0	0
7	5	2	9	7	1	3	2	0	0	3	2
14	0	0	1	0	0	1	0	0	0	0	0
21	3	1	0	6	1	1	3	0	4	3	0
28	0	0	2	1	0	0	0	0	2	1	2
5	4	3	3	13	0	1	0	1	1	2	0
12	0	1	0	3	0	0	0	0	2	0	0
20	0	0	1	4	2	1	1	1	8	10	0
27	0	0	0	0	0	0	0	0	0	0	3
3 January	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	1
23	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0
6 February	0	0	0	0	0	0	0	0	0	3	0
14	2	0	2	1	0	0	1	0	1	6	0
20	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0
5 March	1	0	0	0	4	0	0	0	0	3	0
12	0	0	1	0	0	0	0	1	1	0	0
20	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	1	0	0	0	0	0	0	0
2 April	0	1	0	0	1	1	1	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0

APPENDIX 3

Cydia pomonella 10 mg trap counts during the 1999/00 season in G70 and G5 on Oak Valley Estates, Elgin.

Date	G70					G5				
	Trap number					Trap number				
	1	2	3	4	5	1	2	3	4	5
10 October	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	2	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	7	0	0	0	0	0
10	0	0	0	0	0	0	0	0	1	0
17	0	0	1	3	4	2	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	1	0	0	1	0
8	0	0	0	0	0	0	0	0	3	2
14	0	0	0	2	5	1	0	0	0	2
23	0	0	0	0	0	0	0	0	0	0
4 January	0	0	0	0	2	0	0	0	2	1
12	0	0	0	0	6	1	0	0	0	0
19	0	0	0	0	1	0	0	0	0	0
26	0	0	0	0	6	0	0	0	0	0
2 February	0	0	0	0	1	0	0	0	0	0
9	0	0	1	2	8	0	0	0	1	1
16	0	0	0	0	0	0	0	0	0	0
23	0	0	0	1	5	0	0	1	0	4
1 March	0	0	0	0	0	0	0	0	0	0
8	0	0	0	4	8	1	2	1	16	4
15	0	0	0	0	1	2	0	0	1	1
22	0	0	0	0	1	2	3	2	5	2
29	0	0	0	0	0	0	0	0	0	0
5 April	0	0	0	0	0	1	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0
Total	0	0	2	12	12	11	5	4	30	17

APPENDIX 4

Cydia pomonella 10 mg trap catches during the 1999/00 season in G4B, G4T and G61on Oak Valley Estates, Elgin.

Date	G4B				G4T				G61		
	Trap number				Trap number				Trap number		
	1	2	3	4	1	2	3	4	1	2	3
10 October	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0
10	1	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0
8	1	0	0	0	0	0	0	0	1	0	0
14	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0
4 January	0	0	0	0	0	0	0	0	0	0	3
12	0	0	0	0	0	1	0	0	1	0	0
19	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0
2 February	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	1	0	2
16	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	2	0
1 March	0	0	0	0	0	0	0	0	0	0	0
8	2	0	1	0	1	0	2	0	0	0	1
15	0	0	0	0	1	1	1	0	0	0	0
22	0	0	1	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0
5 April	1	0	0	0	0	0	0	0	0	1	0
14	0	0	0	0	0	0	0	0	0	0	0
Total	4	1	4	0	2	1	1	0	3	3	3

APPENDIX 5

Daily maximum temperatures and monthly average values from 1 November 1993 to 30 April 1994

Day	November 93	December 93	January 94	February 94	March 94	April 94
1	27.8	19.5	23.0	25.6	17.1	24.6
2	24.2	14.3	24.4	17.5	20.9	25.0
3	21.0	17.0	24.4	20.6	19.5	29.4
4	21.2	20.4	32.5	20.6	30.2	32.2
5	25.2	26.1	34.6	25.8	29.9	27.9
6	29.5	19.5	34.0	21.1	23.2	24.8
7	33.6	20.6	28.0	25.7	22.4	29.8
8	23.6	20.0	22.0	31.4	26.0	23.4
9	22.6	19.6	20.1	31.0	31.0	20.9
10	13.7	25.6	21.5	27.7	24.3	28.5
11	15.9	26.7	24.6	23.3	24.8	32.1
12	24.4	33.7	22.4	17.5	23.9	28.2
13	30.1	27.0	17.6	29.5	24.4	33.1
14	25.8	19.9	23.6	30.6	28.4	30.6
15	19.8	30.7	26.8	29.4	31.6	23.0
16	21.7	30.7	30.9	26.2	29.9	20.2
17	27.7	23.0	25.9	25.8	23.9	21.0
18	22.0	21.9	32.1	22.2	28.8	22.5
19	26.8	25.7	29.7	20.3	31.0	20.6
20	26.4	26.2	26.2	25.0	29.5	18.4
21	24.1	25.6	23.9	28.5	26.8	19.8
22	16.4	26.8	18.9	31.2	20.1	19.1
23	17.8	36.8	24.1	34.2	19.2	17.2
24	23.2	28.8	25.4	34.2	20.4	18.9
25	26.4	22.4	30.2	35.8	25.7	25.5
26	29.9	18.0	30.7	34.9	20.2	26.2
27	26.6	21.4	28.2	29.9	22.0	20.2
28	22.4	21.3	23.4	31.3	24.2	15.0
29	26.5	21.8	31.9	***	25.6	17.2
30	23.4	29.3	25.6	***	28.5	21.6
31	***	28.1	29.5	***	21.5	***
Avera	24.0	24.1	26.3	27.0	25.0	23.9

APPENDIX 6

Daily maximum temperature values and monthly average from 1 November 1994 to 30 April 1995.

Day	November 94	December 94	January 95	February 95	March 95	April 95
1	29.5	23.9	24.3	20.1	24.9	28.3
2	37.2	20.7	24.5	28.4	31.0	31.5
3	21.6	25.7	26.9	32.8	28.6	22.3
4	20.9	20.6	33.6	32.4	27.3	20.9
5	23.0	25.9	30.3	36.1	26.4	26.9
6	22.7	20.4	27.2	30.6	21.1	31.8
7	29.8	27.2	16.1	24.5	31.2	27.4
8	22.6	23.2	21.7	25.5	21.2	17.0
9	19.3	15.1	24.8	33.1	26.8	15.3
10	18.8	22.4	29.1	26.5	35.4	23.2
11	19.0	29.2	25.6	24.1	24.2	27.0
12	20.4	34.8	27.7	28.8	22.2	28.3
13	17.5	27.2	29.2	26.8	27.0	27.4
14	16.2	29.2	25.9	23.2	27.8	20.1
15	15.9	31.8	33.1	20.7	34.6	14.7
16	20.2	29.4	25.4	25.5	36.9	18.5
17	20.7	26.2	28.4	30.5	29.6	22.6
18	20.6	27.0	21.9	31.8	15.6	21.6
19	21.2	28.9	28.5	25.8	18.2	13.6
20	20.7	29.0	29.6	20.1	21.1	16.2
21	16.6	24.8	32.0	24.3	25.0	17.6
22	18.4	21.6	28.6	31.4	23.1	20.0
23	17.7	15.8	32.3	30.1	22.5	13.4
24	23.1	17.6	25.2	31.7	23.9	17.1
25	26.0	20.8	23.7	37.1	24.7	14.0
26	25.2	21.8	22.9	33.8	21.6	15.7
27	17.6	24.3	26.7	27.7	21.5	17.2
28	22.8	28.7	22.0	18.0	25.8	18.4
29	30.1	31.5	20.6	***	20.5	22.6
30	28.9	27.2	25.0	***	19.2	25.6
31	***	21.2	23.6	***	22.7	***
Avera	22.1	24.9	26.3	27.9	25.2	21.2

APPENDIX 7

Daily maximum temperatures and monthly average values from 1 November 1997 to 30 April 1998.

Day	November 97	December 97	January 98	February 98	March 98	April 98
1	26.8	22.4	28.4	28.7	26.3	18.4
2	25.6	17.9	35.5	25.2	28.7	25.4
3	22.9	18.5	37.9	25.1	28.6	24
4	32.6	22.2	35	25.7	28.6	23.6
5	20.6	25	31.8	29.7	31.1	19.7
6	23	23.7	20.3	33.1	23.5	20.2
7	26.7	25.5	26.5	27.1	18.8	21.2
8	24	24.6	18.1	27.9	18.6	20.1
9	18.7	24.8	15.6	22.2	19.3	23.4
10	20.9	24.6	20	27.2	21.4	21.9
11	27	28.5	25.6	32.2	20.3	25.2
12	29.4	30.5	25.7	25.1	23	28.1
13	23	23.2	19.2	31.1	29	23.6
14	25.7	24.8	26.8	35.5	32.6	27.5
15	21.1	33.3	27.8	23.5	30.1	30.4
16	14.6	19.7	24.2	23.7	25.6	25.1
17	13.7	15.9	24.2	31.1	29.4	29.4
18	18.5	21.1	22.5	33.6	26.9	29.9
19	22.3	31	22	33.5	29.7	33.8
20	23	32.8	26.4	30.1	25.7	23.1
21	13.5	22.8	25.7	28.2	23.1	22.4
22	16	28.2	24.3	23.5	24.4	15.2
23	18.9	32.7	22.2	25.1	28.1	17.2
24	14.7	23.7	23.6	30.7	24.3	24.2
25	20.2	21.4	30.3	34.8	19.2	24.1
26	22.1	25.4	28	30.8	22.6	22.3
27	23	29.9	33.1	25.8	25.2	23.3
28	24.6	25	26.3	23.5	23	24.6
29	27.7	32.5	22.2	***	30	31.7
30	31.1	34	22.8	***	24.7	21.7
31	***	23.2	27.6	***	22.8	***
Average	22.4	25.4	25.8	28.3	25	24

APPENDIX 8

Daily maximum temperatures and monthly average values from 1 November 1998 to 30 April 1999.

Day	November 98	December 98	January 99	February 99	March 99	April 99
1	20.4	23.6	22.4	21.9	24	32.5
2	15.8	24.5	23.2	18.6	24.4	23.6
3	16.1	30.2	24.9	24.4	27.1	30
4	17.1	36.9	26	30.1	26.9	29.4
5	15.4	29.1	31.1	24.2	22.7	27.6
6	13.8	21.9	24.6	21.5	26.2	26.1
7	19.6	18.5	30.5	24.8	30.5	19
8	27.2	23.6	31.3	28.6	19.2	19.5
9	31.7	25.2	26.4	32.4	27.5	18.5
10	22.5	29.1	18.2	28.1	35.1	24.6
11	26.6	28.1	18.5	29.1	23.5	28.6
12	31.3	28.6	24.1	28.5	17.3	35.5
13	24.3	32	29.1	28.1	25.9	32
14	21.3	20.1	21.8	34	30	27.3
15	20.9	23.1	29.4	32.5	30.8	19.3
16	16.8	21	27.9	29.3	31.4	18.1
17	18.1	25.7	27.5	31.1	26.5	17.9
18	21.9	30.5	25.3	33.4	31.8	13.5
19	17.3	23.4	30.3	25.7	24.9	17.7
20	19.2	21.2	26.8	28.9	18.5	18.3
21	23.6	21.2	33.4	22.9	21.3	17.2
22	29	21.2	33.6	27.1	22.4	18
23	24.5	31.5	27.8	29.2	17.6	18.2
24	17.2	25.3	28.9	27.3	29.1	18.4
25	20.9	22.3	32.4	30.6	28.1	21.7
26	20.8	22.2	32.4	22.9	23.7	27.1
27	25.5	25.1	35.6	26.3	29.6	26.4
28	30.4	23.7	30.4	23.7	36.5	30.2
29	24.9	31.1	21.6	***	33.7	30.1
30	23.2	25.7	31.1	***	34.4	20.2
31	***	21.9	29.3	***	36.5	***
Average	21.9	25.4	27.6	27.3	27	23.6

APPENDIX 9

Daily maximum temperatures and monthly average values from 1 November 1999 to 30 April 2000.

Day	November 99	December 99	January 00	February 00	March 00	April 00
1	26.7	32.8	17	23	19.4	32.9
2	28.1	29.2	20.3	25.5	18.4	25.4
3	30.8	29.6	28.3	32.2	19.5	21.6
4	17	30	32.1	28.4	27.5	21.9
5	23.2	25.7	26.8	26.4	28.5	26.1
6	30	24.8	28.6	29.5	17.6	27.2
7	20.5	29.4	21.5	28.6	24.9	31.8
8	19.9	34.5	24.7	29.1	25.9	23.8
9	25.1	34.7	27.5	35.3	29.8	23.8
10	25.9	32.1	25.3	26.6	26.8	24
11	35.2	34.1	25.9	24.1	25	22.5
12	22.6	32.6	21.2	19.6	27.3	24.7
13	23.3	34.7	25.5	25.4	23	26.2
14	28.6	35.8	25.6	27	19.8	19.8
15	29.5	32.6	26.4	21.8	15.8	26.2
16	35.7	32.6	28.2	29.5	17.3	25.6
17	22	30.9	33	34.7	23.1	24.9
18	15.9	28.4	36.2	38.4	27.5	29.1
19	16.7	21.7	40.1	25.9	25.5	31.6
20	21.4	22.1	40.4	20.6	28.1	29.7
21	27.3	27.3	36.8	28.8	33.3	23.3
22	23.1	30.1	27.8	24.7	27	21.4
23	21.2	22.8	30.9	22	34.1	17.4
24	23.1	24.6	31.7	32.3	22.2	17.4
25	23.1	26.8	28.2	27.2	18.3	15.9
26	19	31.1	29.9	24.6	21.2	17.4
27	19.7	34.2	27.7	27.2	20.9	18.2
28	21	31.1	23.9	32.6	24	23.7
29	26.5	33.1	25.8	25.8	24.8	22.4
30	31.8	24	23.1	***	23.4	20.8
31	***	20.9	22.2	***	26.5	***
Average	24.1	29.5	27.9	27.5	24.1	23.8